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EVALUATION OF GOAL PROGRAMMING
FOR THE OPTIMAL ASSIGNMENT
OF INSPECTORS TO CONSTRUCTION PROJECTS

THESIS

James R. Schnoebelen
Captain, USAF

AFIT/GEM/LSM/88S-16

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# EVALUATION OF GOAL PROGRAMMING FOR THE OPTIMAL ASSIGNMENT OF INSPECTORS TO CONSTRUCTION PROJECTS

THESIS

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

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Requirements for the Degree of

Master of Science in Engineering Management

James R. Schnoebelen, B.S.

Captain, USAF

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## Abstract

The purpose of this study was to evaluate goal programming as a tool to assist the Chief of Construction Management (CM) assign inspectors to construction projects. Air Force construction projects represent a substantial investment. One way the CM can help insure construction projects are cost effective and high quality is through the efficient use of available resources - the abilities and time of his inspectors. Goal programming appeared to be an appropriate method to help assign inspectors so the CM could obtain the most value out of available inspector man-hours.

The evaluation of the model involved developing a general model and applying it to a test organization. The analytic hierarchy process (AHP) was used to translate the preferences and judgements of the CM into a form suitable for a mathematical model. The test confirmed goal programming's ability to represent the inspector assignment problem. The AHP was found to be an appropriate way to translate the CM's desires into model inputs. Despite the success of the model's simulation efforts, a basic difference in the model and the actual decision process was highlighted during the test application. In practice, the CM is constrained to the assignments already made and would

only make additional assignments as new projects begin. Goal programming could still be used within these constraints. However, there are fewer advantages of using a mathematical model when the problem has a relatively small number of decision variables.

The author provides recommendations for continued research in applying goal programming to the inspector assignment decision. However, because of the great deal of effort that would be required to implement a goal programming model, the author's overall recommendation is to concentrate further research on methods other than goal programming. Among the other recommendations provided is to automate the heuristics used by experienced CMs.

EVALUATION OF GOAL PROGRAMMING FOR THE OPTIMAL ASSIGNMENT OF INSPECTORS TO CONSTRUCTION PROJECTS

# I. Introduction

## Importance of Inspection

Inspection of construction methods is an essential part of the total process of constructing a facility by contract (39:314; 2:15).

In the Air Force, the responsibility of managing base level construction projects normally falls under the Base Civil Engineer (11:12-3). In Fiscal Year 1987, base level facility contract projects to construct, repair, and maintain our facilities averaged over ten million dollars per base (56). Inspection is a critical part of insuring the Air Force gets what it pays for in these contracts (42:2).

A 1975 study by the Committee on Inspection of the Construction Division of the American Society of Civil Engineers (ASCE) estimated that nationwide, the costs of poor inspection were over $500,000,000 annually (7:359).

Obviously, causing additional projects costs is not the intent of construction inspection. In fact, there are several ways inspection services can decrease costs including: helping avoid structural failures and project delays, recommending easier and cheaper ways to build, and providing support for avoidance of liabilities and claims (20:63).

It is generally agreed that the benefits of inspection greatly outweigh the costs. K.A. Godfrey said ". . . it's penny wise and pound foolish to save maybe 1/2 to 1 percent of construction costs by shaving inspection. After all, the cost of delays and re-dos if the facility is built incorrectly may be far more than that" (20:62).

Inspection not only can minimize costs, but also improve the quality of construction (39:315). Quality programs using inspections and tests often provide early detection and correction of deficiencies - avoiding scrap, rework, and repair, as well as reduce customer complaints (68:126).

Cost and quality are closely related. Fairweather estimates that "7-1/2% of construction dollars are currently wasted due to poor quality". She feels that for 1 to 1-1/2 percent of total project costs, quality management procedures can be set up that will prevent between 7 - 20 percent of errors on the job (14:64). Iselin considers inspection an important factor in quality because it provides the "the last effective checkpoint in the quality chain" (34:508).

## Justification for Study

Need for Model. Austere funding, reduced manning, and scarce resources make it important for Air Force construction managers (CM) to efficiently and effectively use their resources to accomplish their inspection responsibilities (16:4). Major General Gilbert, former Air Force Director of Engineering and Services believes rapidly increasing costs will require civil engineering squadrons to improve their efficiency through better mixes of resources (19:4). Personnel are the most important resource for many organizations (74:11). In a Construction Management Section, the inspectors represent the primary resources available to the CM.

A 1985 Masters Thesis study by Upshur found that both the Chiefs of Construction Management and the inspectors felt the inspection work load was excessive (84:67-68). However, less manning, not more, is predicted throughout Air Force Civil Engineering (16:4). Additionally, there is some evidence that, within the Air Force, the inspectors' training and qualifications may not be a problem (84:vi).

Therefore, obtaining additional inspectors will not usually be feasible, and the inspectors' abilities are already adequate and relatively unchanging in the short run. So how can the Chief of Construction Management increase productivity and effectiveness of his section to help insure Air Force construction projects are cost effective and high quality? One way to is through the efficient use of existing, available resources (16:12-13) - in the case of the Chief of Construction Management, the abilities and time of his/her inspectors. As mentioned above, both the workers and managers perceive that inspectors are overworked (84:57). However, there is contradicting evidence that the average number of projects per inspector is within the number that can be handled effectively (84:30-31). This may be an indication that inspectors are not being assigned to projects in a manner that provides an efficient and effective use of inspection man-hours.

The day-to-day management of construction inspection, including the assignment of inspectors to projects, usually falls under the Chief of the Construction Management Section (11: 13-2). The organization of the Construction Management Section will described in be Chapter II, along with a detailed description of the inspectors' duties.

Quantitative Models. Currently, the CM must make assignment decisions based purely on his subjective judgement. This research effort evaluates a quantitative method called goal programming (GP) to aid the CM by attempting to assign inspectors in a way that provides the most value out of available inspector man-hours.

The more complex and resource-scarce environment of today has resulted in the development of more refined quantitative techniques and tools to help the decision maker. Managers need both quantitative and qualitative inputs (8:1). However, quantitative models are used to complement the judgement process, not to make decisions (31:2; 43:9). Ignizio describes the importance of the use of quantitative decision methods with the following:

> Despite the claims of "seat-of-the-pants" decision making, divine revelations, and woman's intuition, the human mind is simply not equipped to perform a thorough, systematic, and objective analysis of most of the large and complex decisions that we often face. Consequently, the majority of credible approaches to decision making must employ an aid: a model of the problem under investigation [31:2].

Often just the process of building a quantitative model provides managers greater understanding of the organization's operations and helps prepare them for situations not otherwise anticipated (86:vii; 59:209). Also, once built, they allow decision makers to analyze, mathematically, alternatives which they might not otherwise had been able to evaluate. Similarly, models can be experimented with - allowing evaluation of the effects of certain actions on the organizational system without actually changing the real system (86:vii).

Another motive for quantitative tools is that qualitative skills and judgments are generally gained only through experience, while quantitative abilities can be acquired by study (48:4). If the CM is a relatively inexperienced engineer, as is often the case (15:82; 22:35), he could rely rather heavily on the model until he gains the experience necessarily for more intuitive decisions. The more experienced manager should combine knowledge from the two approaches and compare the information to make the best decision possible (48:4).

Most quantitative models fall under the germane of Operations Research (OR). The application of OR models in management has been growing rapidly (25:5; 50:972). In fact, Hillier and Lieberman believe the impact of the development of OR models in recent years seems to be unrivaled by that of any other development except for the electronic computer (25:5).

The following problem characteristics indicate quantitative analysis may be appropriate:

1. Complex with many variables.
2. Difficult to solve without quantitative tools.
3. Repetitive.
4. Involves numerical data.
5. Quantitative techniques have been used successfully in similar situations (48:4).

The problem of assigning inspectors to projects fits this description closely. It involves a complex mix of inspector and project attributes, resource constraints, and organizational goals. It is a decision that is repeated frequently so the efforts involved with the initial model development and implementation are justified. As will be seen in Chapter III (the model formulation), the inspector assignments do involve numeric data. Finally, quantitative methods, including goal programming, have been successfully used in human resource allocation decisions (51:1447).

Goal Programming. Perhaps the most difficult problems for decision makers to evaluate are those involving multiple, conflicting objectives (43:10). As an example in the decision problem of this study - the goal of training lower grade inspectors must be balanced against the objective of maximizing the quality of completed projects (which would imply the use more experienced inspectors). GP is an appropriate, powerful, and flexible technique for analyzing these type of complex real world decisions (43:10; 52:75).

Additionally, it is often impractical to reduce or aggregate all the objectives of an organization to a single goal to serve as the measurement criterion for a decision. GP allows the manager to determine the optimal decision in situations involving multi-dimensional criteria that are not directly comparable (52:5; 41:196). For example, the benefits of minimal manning might be considered in salary dollars saved, while the value of using experienced inspectors might be measured in terms of customer satisfaction.

GP is a type of mathematical programming. It has been considered both as an extension of, and as a more general form of, linear programming (29:1117). The mathematics of GP will be discussed in Chapter II, but in general,

> . . . a goal programming model performs three types of analysis: (1) it determines the input requirements to achieve a set of goals; (2) it determines the degree of attainment of defined goals with given resources; and (3) it provides the optimal solution under the varying inputs and goals constraints [43:30].

In goal programming, objectives are established with corresponding priorities that reflect the decision maker's priorities (30:xvii; 36:159).

There are other multiple objective models available and GP is not always the best multiple-objective approach (31:12, 374). However, it was chosen for this study for several reasons including:

1. The GP model and its assumptions can provide a practical and realistic representation of real-world problems (29:1117; 31:374).

2. It has been extensively and successfully applied to manpower problems (59:207; 30:2; 31:13-14, 374). GP is considered "one of the mainstreams of analytical techniques for planning human resources" (58:302). In fact, one of the earliest applications of GP was formulated by Charnes and Cooper in 1967 for manpower planning in the Navy (4).

3. A GP model is reasonably simple and straightforward to develop, implement, and use (31:374; 89:143).

4. GP can be modified to include most of the alternative multiple objective approaches (32:332).

5. It can be solved relatively easily (31:374).

6. The use of goals as a model input has management appeal since " . . . decision makers are very often thinking in terms of various goals and aspiration levels in practice" (40:355).

7. Goal programming provides decision makers the capability to evaluate a variety of multi-objective 'what-if' type questions (89:143). This allows him to compare how well goals can be met under different goal hierarchies (57:44) and " . . . facilitates management's assessment of the repercussions of considered actions, the sensitivity of outcomes to assumptions used, the impact of a changing environment, and the relative costs of some goals in terms of others" (59:209).

8. Its great flexibility. This is often considered GP's most important advantage (43:31; 1:56; 31:374). It allows the sensitivity analysis described above (43:31) and also allows users, rather than the model builders, to impose priority structures (1:56).

## Problem Statement

The success of construction projects is often tied directly to the Construction Management Section's ability to control cost and quality of the project through effective inspection. There is a need for a decision model to aid the Chief of Construction Management in determining how to allocate his/her inspectors among the projects so that the benefits of inspection are optimized. The use of goal programming appears to be an appropriate approach to this problem.

## Research Objectives

This research will address the following areas:

1. Could goal programming be used to develop a useful inspector allocation model for the Chief of Construction Management?

2. Are there any similar models or algorithms already in existence?

3. What mathematical form of the GP model should be used?

4. How can the objectives be measured for optimization?

5. How should the objectives be assigned weights and priorities?

6. How can the attributes of the inspectors and characteristics of the projects be included in the model?

7. How should resource constraints be included in the model?

8. How well will the system work in the field?

## Scope and Limitations

This research will be confined to the evaluation of a goal programming decision model for a Air Force Civil Engineering Construction Manager to use in assigning inspectors to base level construction projects.

Although the efficient use of manpower includes behavioral factors such as motivation and job satisfaction, this study will generally only address those factors that can be more easily quantified into a model.

It is not the intent of this research to develop a model in a final form for implementation in the field. It is the initial evaluation of the feasibility and usefulness of goal programming as a method for determining inspector to project assignments.

The use of Architect-Engineer contracts for inspection services is not directly considered in the problem analysis.

This paper does not include a detailed discussion on solution techniques and algorithms. Several texts are available that provide explanations of goal programming solution procedures (30; 31; 43; 53; 76).

## Assumptions

This research will be based on the following assumptions:

1. The manning in the Construction Management Section is constant over the planning horizon of the model.

2. The CM is able to determine the relative importance of the attributes of inspectors, characteristics of construction projects, and the inspector/project assignments.

3. A deterministic model, that is one that does not require the consideration of chance variance and probability distributions, will adequately model the problem.

4. The organization of Construction Management sections do not vary significantly from base to base.

5. The construction inspectors in the Contract Management Section can be represented as a separate resource from the quality assurance evaluators.

6. The responsibilities of the construction inspector are similar throughout the Air Force.

7. The mathematical assumptions necessary for goal programming as described in Chapter II are reasonably consistent with the actual organizational system.

## II. Literature Review

### Construction Inspection

It is critical when developing a model to understand its intricacies by identifying and defining the applicable variables, deciding how to measure them, and examining the interrelationships between them (66:543). For this initial model development, a review of the literature was conducted to better understand the Construction Management decision environment. The review included the organization of the section, the tasks the resources (the inspectors) are required to accomplish, resource attributes that effect the relationships between the expenditure of resources and the attainment of organizational goals, and the relationships between the organization and those elements outside the organization the provide input to project outcome.

Construction Management Section. The Construction Management Section, as used in this research, refers to the function in Air Force Civil Engineering that oversees the work of government contractors providing maintenance, repair, or alterations to existing Air Force Facilities, as well as the construction of new facilities (11:13-1 to 13-2). In actuality, the construction management function is typically one part of the Contract Management section. The other duties of the Contract Management section, including service contract and purchase order administration, are not considered in detail within this research. The Construction

Management Section usually falls under the Engineering and Environmental Branch in the Base Civil Engineering Squadron (BCE) (22:V-4). A typical relationship between the Construction Management Section and the rest of the BCE organization is given in Figure 1. below.

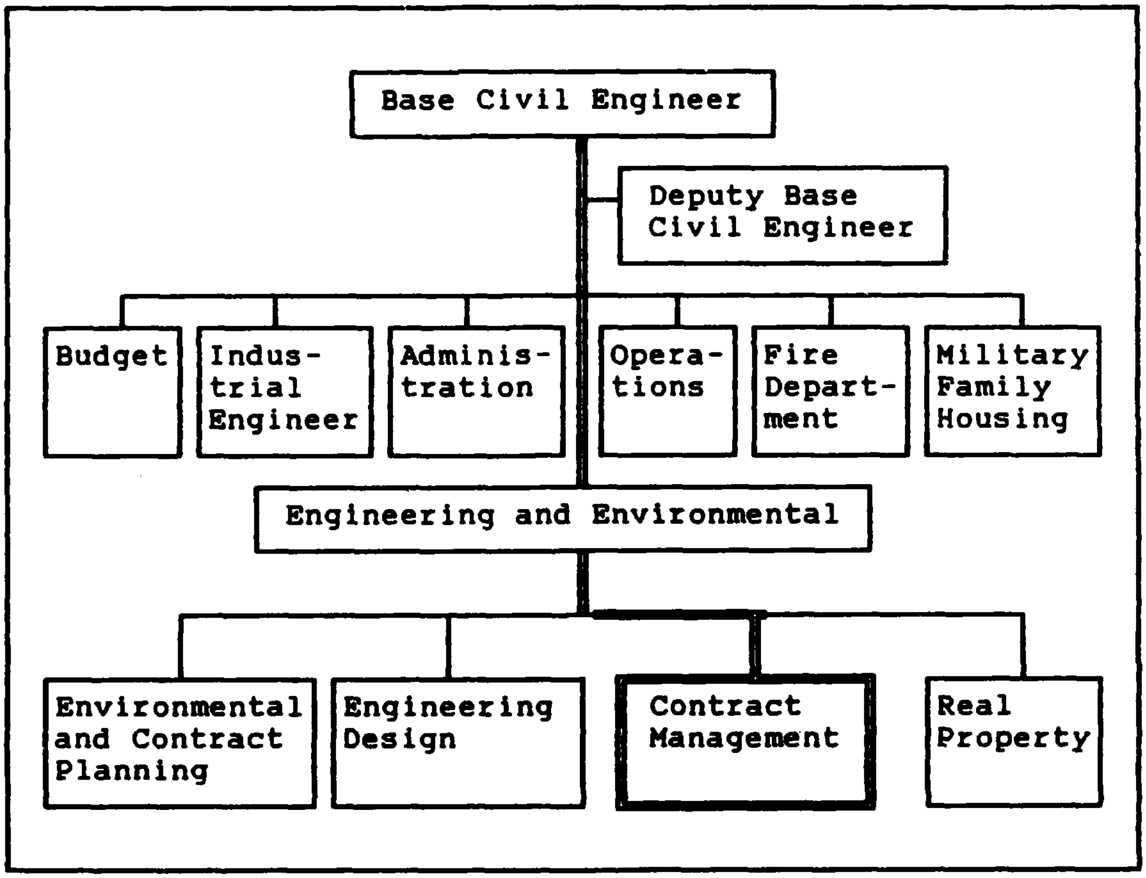


Figure 1. Location of Contract Management in BCE Squadron

<u>Function of Inspection</u>. In general terms, inspection is the function of comparing or determining the conformance of product to specification (38:2). The construction inspector is the individual charged with the inspection of a construction project, including auxiliary duties involved

with contract administration (39:315). His basic function is to assure that the quality of materials and methods of construction used will meet the requirements specified in the contract (21:121).

Inspector Duties and Roles. Probably the most extensive listing of the inspector's responsibilities was given as part of the study by the 1975 ASCE Committee on Inspection report. They describe 19 responsibilities the inspector must assume to accomplish the basic inspection function described above (7:360-362). Since then, most descriptions of the responsibilities of the inspector, including those used for the Air Force inspector, have followed closely to that list.

The Air Force inspector's functions can be broken down into duties directly and indirectly related to inspection (10:4).

The indirect duties include supervisory, administrative, training, and supply responsibilities.

The direct duties of the Air Force construction inspector can be classified into four areas associated with phases of a project: project initiation, contract compliance inspection, acceptance inspection, and warrantee and guarantee programs (10:4-18). These areas are discussed in detail below.

Project Initiation. The inspector assigned to a project reviews all contract documents prior to construction to identify errors in drawings or specifications and to determine if the design features are practical (11:A-29). These reviews are called 'constructibility reviews'. Constructibility recommendations can include "contract packaging, construction sequencing, construction cost, access to work, safety, work rule and jurisdictional effects, construction methods, materials, and minimization of construction interferences, as well as design detail improvements." (82:92).

Before or near the start of construction, the contractor must submit a proposed progress schedule (18:52.236). The inspector evaluates the schedule recommends approval or disapproval of it to the contracting officer (10:6).

Similarly, he recommends approval or disapproval of the contractor's submittals for shop drawings, material and equipment (11:13-3). In both cases the final approval authority is given to the contracting officer, not the inspector. The inspector is only given responsibility to provide technical advice to the contracting officer (11:13-3).

If there is government furnished property (GFP), the contract performance dates are based on the assumption the GFP will be available for the contractor by a specified date (18:52.245). The inspector must maintain close surveillance of the GFP to avoid government caused delays in the contract schedule (11:13-4)

Compliance Inspection. This phase refers to the duties the inspector must perform during the construction process.

Of course, one of his main duties is to perform daily inspections to check for contractor progress, compliance with contract specifications, and to insure contractor meets with the safety requirements of the contract (10:7; 11:13-4).

If the inspector finds noncompliance by the contractor, it is also his responsibility to initiate corrective actions (11:13-4 to 13-5).

Perhaps the most important responsibility for the inspector during any phase of the project, but especially during the construction, is to keep extensive documentation (65:86). The inspector must do daily written reports of work and work conditions. He should document and include in permanent records - meetings, correspondence, written notes of verbal communication (e.g. conferences and phone calls), and any other communications that could be important to the administration of the contract (21:126,147).

Birch recommends inspectors record "every bit of information possible". The information can be used as reference for future performance of the work and legal actions or litigation, and as clues for future investigations (in the event of a facility failure) (2:19).

The documentation tasks also involve maintaining records of construction changes for inclusion in 'as-built' drawings (11:13-2).

The project inspector coordinates any construction activities that affect other base personnel (e.g. power outages, street closings, etc.) (10:8).

Additionally, the inspector is a technical consultant to the contracting officer (11:13-3). Although the inspector or some other Civil Engineering representative will perform this function throughout the project cycle, this role has many inspector duties during construction. For example, his duties include certifying the progress the contractor has made and that the work has been satisfactory. The contracting officer uses this information when making payments to the contractor (23:26). Similarly, the inspector may make recommendations on changes on material substitutions and renegotiation of costs (21:121-126).

The inspector's tasks during this phase may also involve preparing status reports for the CM and other managers (10:8).

<u>Project Acceptance</u>. The acceptance phase includes those actions necessary for the government to accept and take over a new facility. The prefinal, final, and follow up inspections are part of the responsibilities of this

phase (11:14-3 to 14-4). The prefinal inspection occurs several days before the expected completion date. During it, the inspector, along with the contractor and CM, inspect the project thoroughly and record all of the deficiencies. This list is called a punch list. The final inspection is then held after the contractor corrects all items on the punch list (11:14-3 to 14-4).

Post-acceptance inspections, normally conducted between nine to twelve months after physical completion, " . . . are performed to discover latent design or functional deficiencies not apparent before or during the transfer and acceptance of new facilities by the Air Force" (11:14-5).

Other inspector duties in this area include insuring the owners manuals, keys, spare parts, etc are formally transferred to the Air Force and acceptance documentation is properly prepared (11:14-4 to 14-5).

Warrantee and Guarantee Program. The last area of direct project inspector tasks is the warrantee and guarantee program. The inspector helps determine what equipment and other items should be covered be warranties or guaranties. Construction warranties on a new facility are part of an optional clause and if included in the contract begin the date of final acceptance and last one year (18:52.246). The inspector also helps keep track of the items and facilities are under warrantee. Additionally, he investigates facility failures, checks to see if it is still under warrantee and if it is the contractor's responsibility, and follows up on contractor defaults (10:11).

Inspector Capabilities and Characteristics. Many attributes of the inspector effect the value of his inspection to a construction project. Several of these capabilities and characteristics are discussed below.

Job Knowledge. The inspector's level of proficiency is closely related to the amount of knowledge he has gained through practical experience (2:14). Experience in the type of construction involved in the projects he is assigned is especially valuable (39:318). The learning experience should be under the supervision of a construction engineer or experienced construction inspector (7:360). Training programs that continue on a sustained basis obtain the best results (2:23-24).

Along with on-the-job training, the inspector should have " . . . sufficient formal education to give him the capacity to understand the engineering principles involved in the construction of the work he is to inspect . . . " (7:360). This technical training is essential in his ability to perform his duties with a minimum amount of supervision (39:318).

Both of these forms of learning should include not only engineering and construction knowledge but an understanding of the contracting documents and requirements (2:14; 39:318; 82:91).

Personal Characteristics. The personal characteristics of the inspector also effect his inspection competence. Important personal characteristics for an inspector include:

1. Has good judgement based on his experience (2:14; 39:318).
2. Has high integrity (2:14).
3. Is alert and observant (2:14).
4. Merits the respect and confidence of those he works for and of those whose work he inspects (2:14; 7:360).
5. Is honest and fair (7:360).
6. Possesses common sense (2:23).
7. Has the ability to relate to the contractor and his personnel, while at the same time avoiding over familiarity with them (39:318). The inspector should be able to emphasize with contractor's problems and work cooperatively with him to save costs and without compromising conformance to the plans and specifications (2:14).
8. Is " . . mature, confident, patient, [and] meticulous in carrying out his duties, . ." (2:14).

Interfaces With Others. A key step in developing an organizational performance model is understanding how the organization interacts with other elements within the same performance system (79:53). The inspector's interfaces with the design engineers, contractor, and contracting office are described below.

Design. Although part of the role of inspector is to insure design, as submitted, is executed in the field, another primary function of inspection is in recognizing and correcting design errors (3:55). This function is critical since enforcing the execution of a bad design can be just as bad, or worse, than a lack of compliance enforcement.

The inspector can perform various roles in the design phase. He may assist in the formulation of the design itself by assuming responsibility for estimating the costs and performance schedule. The more common role is as an adviser to the designer on the constructibility issues described earlier (82:92).

The benefits of constructibility reviews can be tremendous. More money will be saved and with less effort by catching it early in the design before actually 'building the mistake'. Problems that arise during construction concerning plan errors are more difficult and costly to deal with (65:86; 82:90).

Constructibility reviews can be critical in identifying gross errors and obtaining more 'constructible' projects

(87:10). The inspector should play a major role in developing specifications involving field coordination and control, work simplification, quality management, safety, and labor provisions (82:92).

Besides improved constructibility, potential benefits from constructibility reviews include improving the contracting strategy, fitting design packages into forms amenable to subcontracting plans, and overall project (design, procurement, and construction) schedule integration (82:92).

Contractor. An inspector's behavior can significantly affect the relationship between the contractor, the Construction Management Section, and other government personnel (7:363). The inspector's relationship with the contractor must be a balanced one. The inspector should be agreeable and cooperative with the contractor, yet remain impersonal and avoid familiarity (7:363). If the inspector cooperates with the contractor and helps him in all practicable ways to complete the work economically and satisfactorily, both the government and the contractor should benefit (2:24).

The inspector should not interfere with the contractor's method of doing work. He should advise, but not try to force the contractor to arbitrarily use a particular procedure where specifications permit more than one method (2:25).

Inspector should give direct instructions or formal orders to the contractor or his superintendent only, not to subcontractors or workers (2:25).

Contracting Office. The Base Contracting Office has a major influence on the Contract Management Section's performance level. Civil Engineering relies very heavily on the contracting office's support to complete construction projects (15:2).

The contracting office is responsible for managing all contracting activities to include soliciting, reviewing, awarding, and administering the contracting actions (9:1).

At many bases there is a poor working relation between the civil engineering and contracting organizations (22:V-11; 15:101). Because of the many areas of critical coordination between Civil Engineering and Contracting, this conflict can cause unnecessary costs to the government (22:V-11; 62:1-2 to 1-3).

## Goal Programming

Classification of Mathematical Models. Mathematical models for human resource planning fall into two groups - descriptive and normative. Descriptive models imitate the behavior of the actual organization (64:641). The most common types of descriptive models are Markov models, fractional flow models, renewal models, and simulation models (64:641). They are typically used in human resource planning as forecasting models and to study the effects of alternative policies on the organization (64:643).

Normative models take information from the descriptive models and determine the personnel management decisions that will attain goals in a manner that is optimal according to a stated objective function (64:643). Linear programming and its extensions, including goal programming, are the most frequently encountered normative methods (64:643). They are usually the best approach when conflicting objectives must be resolved or complex constraints must be considered (64:644-645). Goal programming is used when it is necessary to take into account more than one objective (64:643).

History. Goal programming was introduced by Charnes and Cooper in 1961 (5). In 1965, Ijiri presented the idea of preemptive priorities in goal programming (33). Preemptive priorities allow the decision maker to treat goals according to their perceived importance (29:1111). 'Preemptively preferred' objectives are objectives in one priority are that are achieved over the satisfaction of any objectives with a lower priority (29:1111).

During the 1970's and 1980's the available GP solution techniques and areas of applications have grown dramatically (76:4-5).

Solution techniques are currently available for several types of goal programming models, including: non-linear,

linear integer, linear zero-one, interval, interactive, stochastic, and dynamic models (29:1111; 31:484-490; 43:176-185).

Like most management science techniques, GP models must be suitable for computer-based solutions to be beneficial for the manager evaluating complex real-world problems (43:126). Therefore, the rapid development of the computer has helped spur the growth of goal programming and make it more practical for application (76:4).

Basic Concepts. Goal programming allows simultaneous solution to a system of complex multiple objectives. The technique also allows the use of functions composed of nonhomogeneous units of measure.

The two basic elements of a GP model are: a set of goal constraint equations, and an objective function that measures the level of the overall achievement of goals (57:7).

Each objective or goal is assigned a priority that is consistent with the preferences of the decision maker (30:xvii).

Despite the availability of more sophisticated techniques, this research will begin with the basic linear goal programming model for two reasons:

1. The aim in building a model is to start with as simple a model as possible and add to it only if absolutely necessary (31:23).

2. The relative ease of understanding and using linear models makes them preferred to non-linear models in practical applications (13:154).

Extensions of the model to other forms will be covered as their possible applications are discussed.

Definitions. Decision Variable. The decision variables are the unknowns that are "under the control of the decision maker and one[s] that can have an impact on the problem solution" (31:401). It is their values that are determined by the model solution.

Objective. An objective is a relatively general statement (in narrative or quantitative terms) that reflects the desires of the decision maker (31:376). For example to 'minimize costs' or 'maximize quality'.

Aspiration Level. An aspiration level is a specific value associated with a desired or acceptable level of achievement of an objective. Thus, the aspiration level is used to measure the achievement of an objective and generally serves to 'anchor' the objective to reality (31:376).

Goal. An objective in conjunction with an aspiration level is termed a goal (e.g. want to keep costs below $5000) (31:376).

Rigid Constraints. Rigid Constraints are absolute goals that must be satisfied (31:30).

Achievement Function. The achievement, or objective function, measures the level of achievement of the associated goals. Its value changes as a result of changes in the decision variables (31:402).

Goal Deviation. The difference between what we accomplish and what we aspire to is the deviation from our goal (31:376). A deviation variable reflects either the under-achievement (negative deviation and denoted as $d_i^-$) or over-achievement (positive deviation and denoted as $d_i^+$), where $i = 1,2, \ldots ,m$ and $m$ represents the number of goal constraints in the model (31:401).

Differential Weights. Differential weights are "Mathematical weights that are expressed a cardinal numbers" (76:68). Represented as $w_{ki}$, the weight for deviational variable i within the priority k ($k = 1,2, \ldots ,K$; $i = 1,2, \ldots ,m$) (76:67).

Mathematical Form. Using a notation similar to Lee and Shim's (47:34), the general mathematical form of the most commonly applied goal programming model and referred to as "preemptive weighted priority goal programming" (77:247), is

Minimize

$$Z = \sum_{k=1}^{K} \sum_{i=1}^{m} P_k(W^-_{ki}d_i^- + W^+_{ki}d_i^+) \qquad (2.1)$$

Subject to

$$\sum_{j=1}^{n} (c_{ij}x_j - d_i^+ + d_i^-) = b_i; \quad i = 1,2, \ldots ,m) \qquad (2.2)$$

$$x_j, d_i^-, d_i^+ \geq 0 \ (i = 1, 2, \ldots ,m; \quad j = 1, 2, \ldots ,n) \qquad (2.3)$$

where $c_{ij}$ is the technical coefficient of jth decision variable of the ith goal, K = number of preemptive priorities, n = the number of decision variables, and m = the number of constraint equations.

<u>Assumptions/Limitations</u>. A clear understanding of the assumptions and limitations of goal programming is required to effectively apply its approach (43:31). Goal programming requires the following assumptions:

1. The decision maker can establish preemptive priorities and weights for each objective without "significantly affecting the true nature of the problem" (30:8).

2. The assumptions necessary in all linear mathematical technique (43:32-34; 76:77-78):

A. Proportionality. Proportionality means both the value of the objective function and the amount of every resource used in each constraint are proportional to level of each decision variable considered individually (43:33).

B. Additivity. Additivity requires that there cannot be "joint interactions among some of activities of the goal attainment or the total utilization of resources" (43:33). Additivity and proportionality together ensure linearity (43:33).

C. Divisibility. Divisibility implies that fractional levels of decision variables are possible in the solution (43:33).

D. Deterministic. The decision environment is assumed to be static with model parameters that are known and constant (43:33).

E. Finiteness. "It is assumed the resulting values for $x_j$, and $d_i^-$, $d_i^+$, must be finite. That is, we cannot have unlimited decision variable values, resources, or goal deviations" (76:78).

Practical problems that completely satisfy all of goal programming's assumptions are rare. But, GP may still be the **most** applicable technique. It is critical the model user is fully aware of the limitations and approximations involved (43:34).

Besides the assumptions described above, additional limitations of goal programming include:

1. Goal programming, like all quantitative methods, ". . . simply provides the best solution under the given set of constraints and priority structure" (43:31). If the decision maker's priorities are not in congruence with the organizational objectives, the organization will not obtain the optimal solution (44:34).
2. There is a lack of available efficient software for solving some types goal programming problems (54:344).
3. The use of preemptive priorities in GP does not allow trade-offs that cause a small degradation in a high-priority goals but large improvement in a low-

priority objective (67:137). The goal programming model ignores the normal human tendency to let the amount of a resource on hand and the current achievement levels influence a decision maker's aspiration levels (67:146-147).

Previous Applications. One of the first applications of GP was in manpower planning (4), and it continues to be used extensively in human resource planning (58:302). Included below are some of the previous goal programming and other quantitative modeling applications reviewed to evaluate their usefulness in the inspector assignment problem.

Arthur and Ravindran used a zero-one goal programming model to schedule nurses. They used GP to allow decision makers to choose their own priorities because they felt weakness of previously used methods was that the model builders, not the users, determined the own priority structure of the model (1:56).

Choypeng, Puakpung, and Rosenthal used a combination of linear programming (specifically, a transportation type model) and integer programming to assign draftees to branch Naval Bases then determine the optimal routing of ships from branch bases to a main base (6).

Holloran and Byrn successfully implemented a computerized manpower planning system for scheduling shift work at an airline's reservations offices and airports.

They too used integer and linear programming. Additionally, they included a network optimization. Their system saved the airline over $6 million per year (26:39-50).

The integer goal programming model Lee, Franz, and Wynne used for State Patrol allocations was solved by the branch and bound procedure (45).

McClure and Wells also used a integer goal programming model. It included input from the sales representatives, in the form of preference values, along with organizational goal values from the management (55).

The optimal assignment of teachers to schools was modeled by Lee and Schniederjans by applying the multi-criteria methodology to an assignment problem. Essentially, it is an zero-one goal programming model where the goal of assigning each teacher exactly one school is the first priority (46).

An automated personnel assignment process for the Navy was developed by Liang and Thompson. The model used a network model to optimize this large-scale, multiple objective problem (49).

Niehaus' book described the Personnel Resource Allocation Model (PRAM) (58:235). The model's purpose was to assist in examining individual person-job assignments in light of constraints of project accomplishment, available personnel, and budget. He assumed personnel are interchangeable (58).

Korhonen and Laakso used an interactive GP method called the Visual Interactive Approach. In this method, the decision maker evaluates attainable solutions corresponding to his goal levels using computer graphics (40).

In their Masters thesis, Moreno and Utz built a GP model for contingency planning that assigned skills and time periods and included priorities (57).

Saladin used a queuing model and input the results into trade-off and regression curves. This information was then input into a goal programming model (75). His model allocated patrol vehicle hours on a per day, per watch, and per precinct basis. Finally, it minimized deviations required to satisfy managerial, budgetary, and performance measurement goals (75).

A model for allocating the academic faculty at a university by Soyibo and Lee used regression and Markovian analysis to obtain the goal equation coefficients (81).

Taylor, Moore, and Clayton developed a model for research and development project selection (83). They felt goal programming was an appropriate modeling framework, but a completely linear model was not always realistic (83:1150). They demonstrated this limitation could be overcome by using a nonlinear integer goal programming model for their project selection and manpower allocation problem (83).

A simulation model was used by Henderson, Krajewski, and Showalter to integrate the staff sizing and the staff scheduling decisions for a service sector organization. They used goal programming as part of the staff scheduling model. Their approach was then applied in a postal processing example (24).

Other examples of the use of goal programming in manpower allocation are included in lists of goal programming applications in references (30:2), (29:1112), and (76:7-20).

### Analytic Hierarchy Process

The Analytical Hierarchy Process (AHP) is a decision method that uses a hierarchic structure to represent a problem (70:157). It is used in this thesis for the ranking and weighting of goals and objectives, and for the calculation of the technical coefficients $c_{ij}$. A brief description of the AHP and its application to determining priorities, weights, and coefficient values is given below.

> Basically the AHP is a method of breaking down a complex, unstructured situation into its component parts; arranging these parts, or variables, into a hierarchic order; assigning numerical values to subjective judgements to determine which variables have the highest priority and should be acted upon to influence to outcome of the situation [69:5].

The steps to use the AHP include:

1. Construct a decision hierarchy with the decision problem represented by a hierarchy of interrelated decision elements.

2. Obtain judgements of the relevant contribution of each element by pairwise comparisons of decision elements.

3. Estimate the relative weights of decision elements.

4. Aggregate the relative weights of decision elements to determine weights for each of the decision alternatives (88:96).

The first step, defining the problem in the form of a hierarchy, is perhaps the most important aspect of the AHP (88:96). The highest level in the hierarchy is the overall objective. The bottom elements are the alternatives that contribute toward the quality of the decision through their impact on intermediate criterion. Elements in the intermediate levels represent the basic criteria for evaluating objectives and other criteria (69:15). Higher level elements usually have higher priorities and are less detailed than lower level attributes (69:84; 88:97). A well constructed problem will generally have no more than five priority levels (30:182). A general hierarchy structure is shown in Figure 2.

A pairwise comparison is merely the evaluation of alternatives, two at a time, against a criterion. Usually the best method to make pairwise comparisons is through the use of matrix like shown in Figure 3 (69:76).

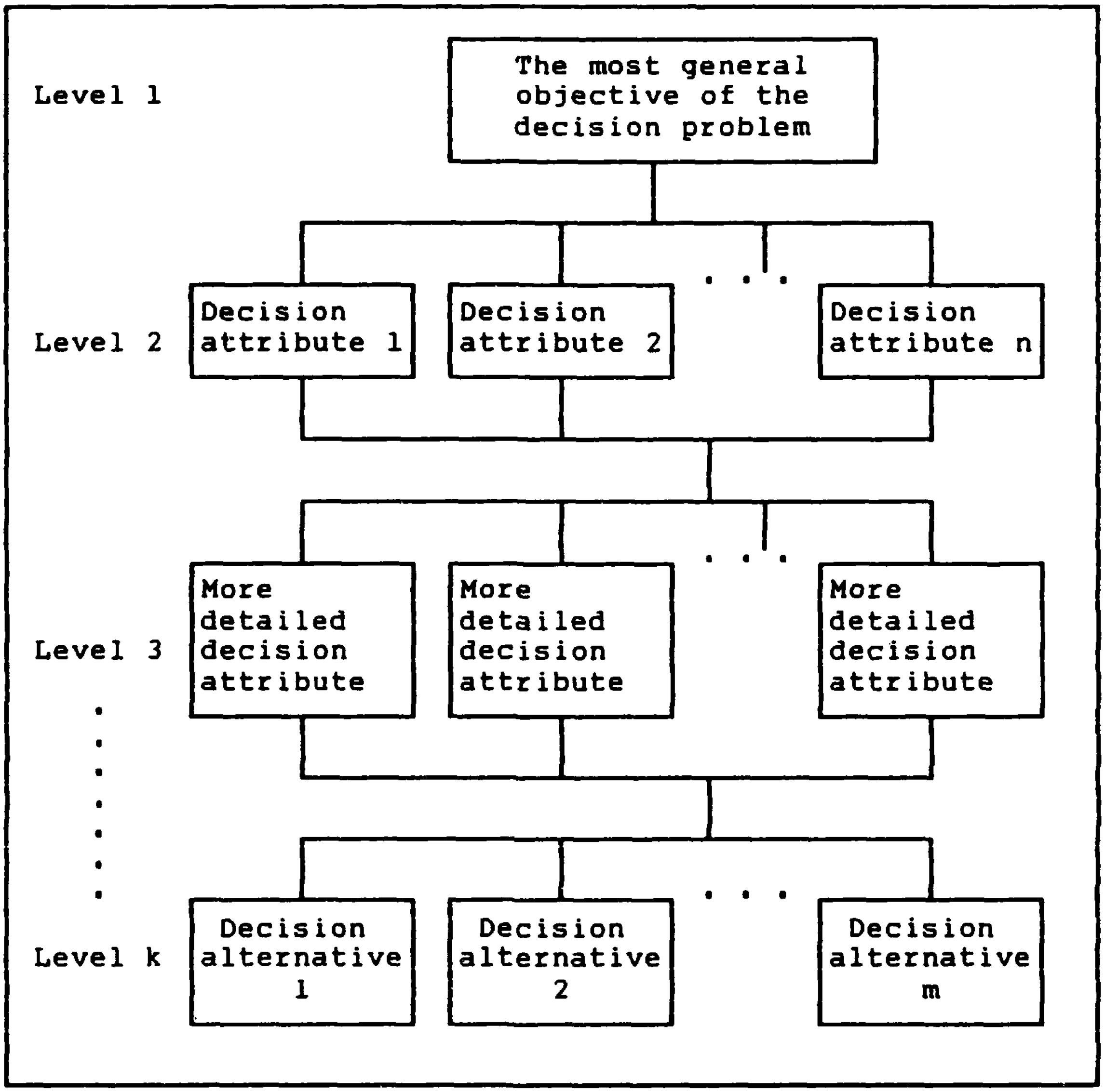


Figure 2. General Form of the AHP Hierarchy with k Levels (88:97)

Saaty describes the pairwise comparison procedure as follows:

> In this matrix compare the element $A_1$ in the column on the left with the elements $A_1$, $A_2$, $A_3$, and so on in the row on top with respect to the property C in the upper left-hand corner. Then

repeat with column element $A_2$ and so on. To compare elements, ask: How much more strongly does this element (or activity) possess - or contribute to, dominate, influence, satisfy, or benefit - the property than does the element with which it is being compared [69:77]?

| C | $A_1$ | $A_2$ | $A_3$ | . . . | $A_n$ |
|---|---|---|---|---|---|
| $A_1$ | 1 | | | | |
| $A_2$ | | 1 | | | |
| $A_3$ | | | 1 | | |
| . | | | | . | |
| . | | | | . | |
| . | | | | . | |
| $A_n$ | | | | | 1 |

Figure 3. Sample Matrix for Pairwise Comparison (Saaty, 1982:77)

In application, typically a single evaluator determines the input data (88:102).

After judgments are made in the pairwise comparisons, the weights are calculated by the 'eigenvalue method' of deriving ratios from a matrix of values (71:33-34,258).

Finally, the process is extended to the entire hierarchy. The weights are aggregated to obtain a single number for each alternative (69:85-86).

There are many methods of obtaining priorities and weights. However, there is little agreement as to which methods are the best (61:182). It was felt the use of the

AHP in this research was appropriate because of the following characteristics of the method:

1. It does not require alternatives that have the same measurement scale for their relative contributions. It not only allows you to 'compare apples to oranges', but also lets you aggregate dissimilar elements (69:21).
2. The AHP provides a way to analyze resource allocation problems involving criteria that can be only indirectly measured (69:196). Also, the judgements on the intangible criteria can be incorporated with ones with known measurements (70:157).
3. The analytic hierarchy process reflects the human decision making process. "It incorporates both the qualitative and quantitative aspects of human thought: the qualitative to define the problem and its hierarchy and the quantitative to express judgments and preferences concisely . . . " (69:18). Additionally, the decision makers who structure the hierarchy also supply the comparison judgements (69:74).
4. The AHP goes beyond just simulating the way the decision maker thinks, it improves it by helping speed up the thought processes and by identifying factors that might not ordinarily be considered (69:24).
5. It is a proven method with confirmed validity (69:120).

6. The AHP can test the consistency of the decision maker's judgements. For example, if the CM says project A is more important than project B and project B is more important than project C, he is consistent if he also feels that project A is also be more important than project C. The AHP also tests the consistency of the **intensity** of his ratings. That is, if project A is four times as important as project B and project B is twice as important as project C, then project A should be eight times as important as project C (71:7). "The consistency is perfect if all judgements relate to each other in a perfect way" (69:16). The AHP evaluates consistency by the calculation of a number called the consistency ratio. If the value of the consistency ratio is greater than 10 percent, it is an indication there may be a need to revise the judgements or hierarchy structure (69:16-18,83).

Ranking and Weighting. As described earlier, goal programming requires the decision maker to establish priorities and weights for his goal objectives.

As a starting point, Ignizio suggests first rank all objectives, then group objectives according to priorities, and lastly assign weighted factors to the objectives within each priority level (30:182)

It is the proper determination of these weights and priorities that has always been a concern of goal programming applications (17:779).

The typical approach is for the model formulator to select weights by using the judgement and experience of the decision maker "so that somehow the weights reflect the priorities of the various goals" (17:779-780).

Saaty feels the best way to translate the decision maker's judgement into a quantitative measure is through a systematic procedure, like the AHP, that uses paired comparisons (71:64).

Gass believes the coefficients obtained through the AHP can be interpreted as weights that reflect the importance of each alternative. These weights can then be directly used as weights in the goal programming objective function, or first translated to a different scale and then used (17:783).

In a very similar manner, the AHP gives you the rank order of the alternatives by their relative standings on a ratio scale (70:157).

Technical Coefficients. The AHP can also be used to determine the coefficients required in the goal functions (72:333).

An established and frequently used method of determining a measurement scale based on the decision maker's judgement is through the use of utility concepts (37:130).

A utility is the measure of the decision maker's judgement of the impact of an alternative on an outcome (53:815). The weighting factors within the utility function reflect the relative contribution from each performance criterion in the organizational system's overall performance (79:199).

From these weights, a function can then be developed that depicts the relation of the utility to the performance outcome (53:823). In this research, the outcome is the relative attainment of the goal functions. Detailed discussions on the use and development of utility functions can be found in Keeney and Raiffa (37).

However, the task of developing appropriate utility functions is not an easy one. For example, Marini concludes:

> Unfortunately, the use of utility concepts to develop a numberical [sic] weighting function that accurately represents a decision maker's subjective preference structure is a difficult and often impractical task in the real world [52:38].

The analytical hierarchy process has been used to help overcome this problem. Utility functions can be derived from the ratio scales determined from the AHP's pairwise comparisons (85:391). In this way, the model can be more realistic by including the decision maker's judgements on the intangible factors. Additionally, the consistency of the judgements can be tested and verified.

This paper will use the relatively simple methodology suggested by Hughes for deriving utilities using the AHP (28:394). His method transforms the weights resulting from the pairwise comparisons into utilities by the following equation:

$$u = a + bw \tag{2.4}$$

where

$$b = 1/(\text{best} - \text{worst}) \tag{2.5}$$

$$a = -b * (\text{worst}) \tag{2.6}$$

best = the highest weight from the AHP results

worst = the lowest weight from the AHP results

# III. Model Formulation

## Overview

The development of a mathematical model is a balance between remaining simple enough so that it is easily used and understood, yet sophisticated enough to capture the major relationships impacting the system's outcome (31:23; 64:640-641). The more accurately the model reflects the critical relationships of the decision environment, the better the results from decisions based on the model (31:2).

Five steps were used to formulate and build the linear goal programming model (adapted from 30:11-25 and 31:22-40,381-382):

1. Determine model purpose.
2. Formulate baseline model.
3. State general mathematical form.
4. Convert to a multiple objective model.
5. Evaluate and validate model.

A continual part of the process is an attempt to find ways to simplify the model (30:11). This chapter presents steps 1, 2, 3, and 4 along with an example to help clarify the model formulation. A discussion of the model evaluation and validation is given in Chapter IV.

## Model Purpose

The purpose of this model is to evaluate the use of goal programming as a tool used by the CM to optimize the assignment of inspectors to projects. The model was intended to be capture the basic decision characteristics of the inspector assignment decision without including organizational unique parameters.

As part of that desire for flexibility, the model includes the CM's judgements as inputs. Including the model user's qualitative judgement in the decision should help the resulting model more closely reflect the unique situations at each base and improve its acceptance for implementation (46:76). In a complex decision environment like the Construction Management Section, the decision maker's inability to analyze all the factors makes it appropriate for him to use some subjective analysis (43:10). Finally, because Civil Engineering is a service organization, there are many qualitative measures of performance that are difficult to accurately measure, yet must be subjectively included in the model (78:18).

## Baseline Model

The second step was to formulate the baseline model. The baseline model is the "initial, unified mathematical model of a problem" (31:18). The construction of the baseline model involves three steps: determining the decision variables, formulating all pertinent objectives and/or goals, and isolating the rigid constraints from the list of goals (31:27).

Decision Variables. The selection of the proper decision variables is critical since they form the basis for the rest of the model development (30:11).

The decision variables are the model parameters that the decision maker can control (30:12). Factors that effect the outcome of a construction project, but are not within the CM's control, were not included in the model. This eliminated factors such as the quality of the design and specifications, budget constraints, experience and expertise of the contractor, and the amount of assistance by the design engineers (78:19).

Factors that are under the CM's influence include: "Balancing the work effort, prioritizing work, seeking additional help, and the use of technical and administrative aids . . . " (63:27-28). A constant level of manning was one of the assumptions of this research effort, so the use of additional help was not included in the model. The use of technical and administrative aids was not directly accounted for in this model because of the difficulty in quantifying them. Additionally, it was the author's belief that although these aids can affect construction projects' outcomes, their inclusion would not significantly alter the optimal assignment of inspectors.

Remaining factors under the CM's control involved the CM's capacity to assign the workload among the inspectors and determining what projects and duties associated with inspecting those projects should be considered the most important. The workload decision variable was designated $x_{ip}$, the amount of hours inspector i dedicated to project p. The work priorities were included in the ranking and weighting of goals that is part of step 4 and the development of the goal equations in step 3.

The best approach in developing a model is to begin with as simple a model as possible by minimizing the number of variables and other factors in the model (31:23). Even though the decision variables were narrowed down to just $x_{ip}$'s, the number of decision variables in the model will grow rapidly. If I = the number of inspectors and P = the number of projects, the number of decision variables will equal I * P. The Air Force average is approximately six projects per inspector (84:30) with 12 to 15 projects considered common (22:69). A model for a base with ten inspectors might have over 100 decision variables. It was decided limiting the decision variables to $x_{ip}$ with a single period planning horizon was desirable. It was also decided that, at least initially, a multi-period or non-linear model would not be used. Assignments, workloads, and project and inspector attributes over the period would be constant.

Goals and Objectives. Objectives and goals fall into three classes:

1. The desires (or aspirations) of the decision maker.
2. Limited resources.
3. Any other restrictions either explicitly or implicitly placed on the choice of decision variables (31:29).

Ignizio recommends to "first simply list those objectives and goals associated with each class" (31:29).

The desires for the CM as the decision maker for this model were assumed to be related to providing the optimal benefits of inspection of projects for the inspection hours available. This overall objective was represented by the more easily quantified objectives 'maximize quality', 'minimize costs', 'provide adequate training', 'minimizing inspector slack time', and 'maintain high job satisfaction'. Although all the benefits of inspection described in Chapter I could be included.

The class of objectives dealing with limited resources would include: limited man-hours, limited inspector experience and skills, limited budget, and a limited number of personnel.

The class of restrictions "are typically goals associated with an attempt to satisfy various 'legal' or physical restrictions . . . " (31:29), these could include:

1. The total man-hours per inspector is greater than zero.

2. The maximum man-hours per inspector.

3. The maximum number of projects per inspector.

4. The minimum man-hours per inspector.

5. The minimum inspection hours per project.

6. The maximum of number of inspectors per project.

After listing the objectives and goals, they were reviewed to try to minimize the number of total objectives. Obvious redundancies or dominated objectives were removed and some objectives and goals were combined. Objectives of minor or negligible importance were eliminated (31:30).

The minimize costs objective was eliminated for two reasons: first, because of the close correlation between cost savings and increased quality due to inspection, they were somewhat redundant. Secondly, the majority of the measurable cost of inspection is the inspectors' salaries, a basically unchangeable cost within the model's planning horizon.

Similarly, the limited budget cost, number of inspectors, and inspectors' skills and experience goal constraints all were eliminated because they were redundant to the available inspectors man-hours constraint and could be combined with it without significantly affecting the inspector assignment problem.

The only goal eliminated from the third class of objectives and goals was the maximum of number of inspectors per project. Although having a maximum of, say two inspectors per project (the primary and alternate) is a valid goal, it was not included in the baseline model to try to keep the number of constraints to a minimum and to avoid having it become a zero-one linear goal programming model. If, in practice, the model assigns several inspectors to one project, this constraint could be added. Finally, the maximum man-hours and the maximum number of projects per inspector were combined with the constraint of available man-hours.

Absolute Constraints. Next the rigid constraints, "those goals that must absolutely be satisfied" (31:30), were determined from the goals above. Goals should be designated as a absolute goal "only if its nonachievement would render the resulting solution unimplementable in actual practice" (31:30). The basic rule is - "if in doubt, do not designate a goal as absolute". The following were selected as the absolute goals:

1. Maximum man-hours per inspector.
2. The total man-hours per inspector is greater than zero.
3. The minimum inspector hours per project.

In summary, the baseline model's goals and objectives are:

Objectives:

Maximize quality.

Provide adequate training.

Maintain high job satisfaction.

Rigid Constraints:

Maximum man-hours per inspector.

Minimum inspector hours per project.

The total man-hours per inspector is greater than zero.

Goal Constraints:

Minimum man-hours per inspector.

## General Mathematical Form

The next step was to translate the decision variables, goals, and objectives given above into mathematical equations that are consistent with the purpose of the model. The usefulness of a model is based on its ability to predict the relative effects of the alternative courses of action with sufficient accuracy to permit a sound decision, not on calculating correct (or even approximately correct) absolute values (25:773). "Therefore, it is not necessary to include unimportant details or factors that have approximately the same effect for all the alternative courses of action considered" (25:772-773).

The first objective, 'maximize quality' equates to maximizing benefits of inspection. This was put into a mathematical form using by assigning a coefficient to each $x_{ip}$ that represents the value per hour of the assignment of inspector i to project p. This coefficient was named 'inspection utility' and designated $c_{ip}$. The equation to maximize quality was then written as:

$$\text{Maximize } \Sigma(c_{ip} * x_{ip}). \tag{3.1}$$

This formulation fits in with the purpose of the model in that it is directly related to inspector assignments and flexible enough to model a general decision. It takes advantage of one of goal programming's strong points - its ability to allow users, not model builders to impose their preferences and judgments (46:76; 1:56).

The determination of $c_{ip}$ would be best made by the individual CMs who can input their qualitative judgments into it to take into consideration the uniqueness of each base, inspector, and project. For the purposes of this research, the value of $c_{ip}$ was calculated by constructing a utility function based on the AHP results as described in Chapter I. However, they were multiplied by a factor of ten since ideally each coefficient should be of a magnitude between 0 and 10 (86:33). The example presented at the end of this chapter further describes this method.

The job satisfaction and adequate training objectives along with the minimum man-hours goal constraints were combined into one equation that represents the total number of man-hours each inspector is assigned. This is consistent with the desire to relate the achievement of objectives and goal to the assignment of inspectors to projects. Additionally, the number of constraint equations can be kept at a minimum by allowing the CM to determine the number of man-hours each inspector should work for job satisfaction, training, job proficiency, etc. Additional functions could be added to the baseline model if they appear to sufficiently represent the CM's goals. The mathematical form of this would be:

$$\sum_{p=1}^{P} x_{ip} = b_i \tag{3.2}$$

where $b_i$ is the total inspection hours aspiration level for inspector i.

The translation of the rigid constraints to mathematical equations is the final process, these are represented by:

$$\sum_{p=1}^{P} x_{ip} \leq MAX_i \quad (i = 1, 2, \ldots, I) \tag{3.3}$$

$$\sum_{i=1}^{I} x_{ip} \geq MIN_p \quad (p = 1, 2, \ldots, P) \tag{3.4}$$

$$x_{ip} \geq 0 \quad (i = 1, 2, \ldots, I;\ p = 1, 2, \ldots, P) \tag{3.5}$$

where $MAX_i$ is the maximum man-hours per inspector and $MIN_p$ is the minimum inspection hours per project.

To summarize, the general mathematical form of the baseline model is:

Maximize

$$Z = \Sigma(c_{ip} * x_{ip}) \quad (i = 1, 2, \ldots, I;\ p = 1, 2, \ldots, P) \tag{3.1}$$

Subject to

$$\sum_{p=1}^{P} x_{ip} = b_i \quad (i = 1, 2, \ldots, I) \tag{3.2}$$

$$\sum_{p=1}^{P} x_{ip} \leq MAX_i \quad (i = 1, 2, \ldots, I) \tag{3.3}$$

$$\sum_{i=1}^{I} x_{ip} \geq MIN_p \quad (p = 1, 2, \ldots, P) \tag{3.4}$$

$$x_{ip} \geq 0 \; (i = 1, 2, \ldots, I; \; p = 1, 2, \ldots, P) \tag{3.5}$$

<u>Conversion to Multiple Objective Model</u>

After the baseline model is formulated and put into a general mathematical form, it must then be converted into the linear goal programming form. Ignizio lists four parts to this step:

1. Decide on aspiration levels for every nonabsolute objective.

2. Add deviation variables to each goal and constraint.

3. Determine the preemptive priorities and weighting factors of the goals (the rigid constraints must be the first priority).

4. Formulate the achievement function, including associating the preemptive priorities with their respective goal(s) (30:16; 31:381-382).

<u>Aspiration Levels</u>. The aspiration levels for the goal constraints are simply the right hand side (RHS) values of the functions. These values would be the CM's desires based on his knowledge of the organization. For example, he may decide that a certain inspector should try to inspect approximately 90 hours per three month period. The RHS values for the rigid constraints are also based on the CM's

judgement. These RHS values, however, are not aspiration levels but absolute limits that the CM feels must be met. For instance, he may believe that no inspector should ever spend more than 150 hours inspecting per period.

The objective maximize $\Sigma(c_{ip} * x_{ip})$ is converted to a goal constraint by assigning it an aspiration level. This level is designated Umax. It can either be assigned a value the decision maker feels is adequate based on his experience and judgement or to a level that equals the highest possible value that can be reasonably reached. In this case, it is assigned the highest value because there is no historical justification for determining what a proper value would be (although it may be possible to use historical records to estimate an appropriate value). The example which follows later in this chapter shows how this value might be calculated.

__Add Deviation Variables__. The second step is merely adding the deviation levels to the goal constraint equations so that they now become

$$\Sigma(c_{ip} * x_{ip}) + d_1^- - d_1^+ = \text{Umax} \quad (i = 1, 2, \ldots, I; \; p = 1, 2, \ldots, P) \quad (3.6)$$

$$\sum_{p=1}^{P} (x_{ip} + d_q^- - d_q^+) = b_i, \quad (i = 1, 2, \ldots, I; \; q = i+1, i+2, \ldots, I+1) \quad (3.7)$$

__Preemptive Priorities and Weights__. The priorities and weights can be selected by the CM using the AHP as described in Chapter II.

The differential weights assigned deviation variables associated with the same goal constraint need not be equal. There is often "a considerable psychological difference between the over- and under- attainment of a goal" (4:195). For example, it may more important for an inexperienced inspector to avoid inspecting too little compared to too much, because it is more important for him to get training and experience.

Achievement Function. The final step in model development is the derivation of the achievement function. This involves selecting which of the deviation variables will be included in the achievement function. For example, the overachievement of the quality goal would not be included in the objective function since presumably the decision maker would not want to minimize the amount the quality value is goes above the target value. Also, the weights determined above must be assigned to the associated deviation variable.

The final model form then becomes

Minimize

$$Z = \sum_{k=1}^{K} \sum_{q=1}^{m} P_k(W^-_{kq}d_q^- + W^+_{kq}d_q^+) \qquad (3.8)$$

Subject to:

$$\Sigma(c_{ip} * x_{ip}) + d_1^- - d_1^+ = Umax$$

$$(i = 1, 2, \ldots, I; \; p = 1, 2, \ldots, P) \qquad (3.9)$$

$$\sum_{p=1}^{P}(x_{ip} + d_q^- - d_q^+) = b_i \quad (i = 1, 2, \ldots, I;$$

$$q = i+1, i+2, \ldots, I+1) \qquad (3.10)$$

$$\sum_{p=1}^{P} x_{ip} \leq MAX_i \quad (i = 1, 2, \ldots, I) \tag{3.3}$$

$$\sum_{i=1}^{I} x_{ip} \geq MIN_p \quad (p = 1, 2, \ldots, P) \tag{3.4}$$

$$x_{ip} \geq 0 \quad (i = 1, 2, \ldots, I; \quad p = 1, 2, \ldots, P) \tag{3.5}$$

## Example Problem

Background. Lt Matt A. Matickle is the Chief of Construction Management at Linear Air Force Base. He is currently responsible for five construction projects totaling 5.8 million dollars and has three inspectors working for him.

Inspectors. The three inspectors - Carl, Hank, and Keith, have varying degrees of experience, expertise and other attributes as described below.

Carl. As NCOIC, Carl is responsible for providing training and supervision to his two subordinates. Carl, a Master Sergeant, has a good overall construction background with a great deal of experience in the area of pavements. He is also the only inspector with the RTS (Really Top Secret) clearance that enables him to inspect within the secure areas on base without special escort.

Hank. Hank, a GS-9, is a retired refrigeration technician. In addition to his mechanical expertise, Hank has quite a bit of practical experience with electrical power, although he does not have much background with electronics. Because of a past drinking problem, Hank does not have a security clearance and is not allowed in any of the secure areas without special permission.

Keith. A bright young Sergeant, Keith is a computer whiz and although he doesn't have much training or experience in the construction field, the Lieutenant feels Keith has a lot of potential for his Air Force career. He has a NSTS (Not So Top Secret) clearance that allows him to work in the secure areas on base if he is escorted. Getting escorts requires a two week prior notice.

Projects. The different characteristics of the five projects are given in the following brief summaries.

Pave Roads. A large ($5 million) contract to construct a six lane 'loop' around Linear AFB.

Install (HVAC). Replaces the complete Heating, Ventilation, and Air Conditioning (HVAC) systems of several buildings on base. Project cost is 400 thousand dollars.

Install TEMPEST. This 100 thousand dollar project is to install an electronic shielding system in one of the buildings in the secure area. It is mostly high tech, electronic work.

New Computer. This is a new computer for the Civil Engineering Squadron. It involves mostly equipment installation and some electrical distribution.

Renovate NCO Club. A high interest, 200 thousand dollar, contract to completely renovate the NCO Club.

Problem Formulation. The assignment of inspector i to project p is represented as $x_{ip}$ with i and p assigned as shown in Figure 4.

| INSPECTOR i | PROJECT p | | | | |
|---|---|---|---|---|---|
| | Pave Roads | Install HVAC | TEMPEST | New Computer | Renovate NCO Club |
| Carl | 1,1 | 1,2 | 1,3 | 1,4 | 1,5 |
| Hank | 2,1 | 2,2 | 2,3 | 2,4 | 2,5 |
| Keith | 3,1 | 3,2 | 3,3 | 3,4 | 3,5 |

Figure 4. Assignment of i and p for Example Problem

Using a one month planning period, Lt Matickle decides that he wants every project inspected at least 20 hours a month. Additionally, he decides on the absolute maximum inspection hours per month and target hours per month for each inspector as shown in Table 1.

Table 1. Maximum and Target Inspection Hours per Month

| Inspector | Maximum Hours | Target Hours |
|---|---|---|
| Carl | 100 | 25 |
| Hank | 140 | 125 |
| Keith | 160 | 80 |

__Priorities and Weights__. Lt Matickle first decided that the quality goal should be maximized to at least 75 percent of the maximum possible (within the absolute constraints), even at the expense of other goals. He therefore placed it at the highest preemptive priority. The other goals, the target inspection hours, were all placed within the second priority level. Using the AHP, Lt Matickle then did a pairwise comparison of the deviations from the second priority goals. The hours inspector i is under- or over-assigned are designated $d_i^-$ and $d_i^+$, respectively. Figure 5 shows the simple hierarchy that could be used to show the relationships of the second priority target hours goals to the attainment of the overall objective.

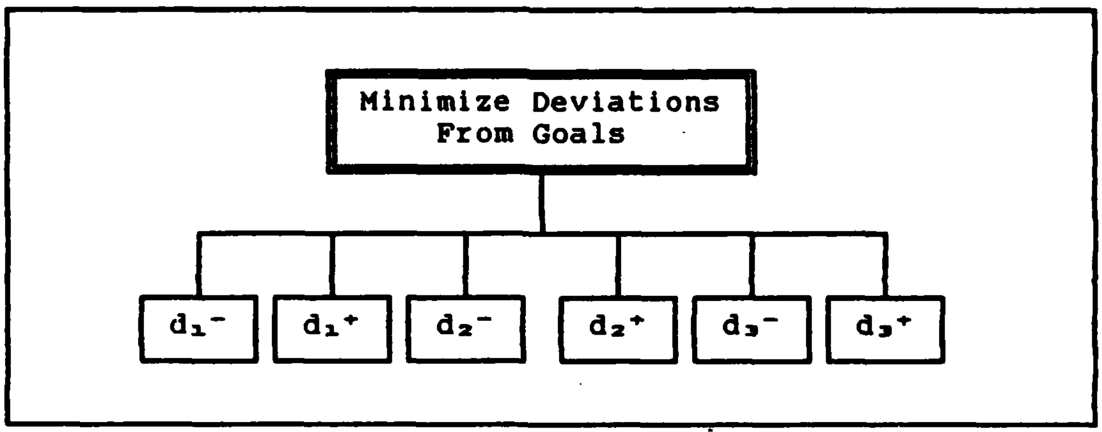


Figure 5. A Hierarchy for Second Level Goals

Figure 6 shows the pairwise comparisons of the importance of avoiding deviations from these goals. A scale of one to nine is used as recommended by Saaty (69:77). In this scale, a one indicates that the row element (the deviation variable along the left side) is 'equally important' as the column element (the deviation variable along the top) it is being compared to. Similarly, a three signifies the row element is 'moderately more important', a five means the row element is 'strongly more important', a seven means the row element is 'very strongly more important', and a nine signifies the row element is 'extremely more important' than the column element. Reciprocal values are used when the column element is more important than the row element. For example, because Lt Matickle wanted to make sure Keith got enough practical experience, he weighted avoiding giving Keith too little inspection work versus too much inspection, as 'strongly to extremely more important'. So, when comparing the importance of $d_3^-$ to $d_3^+$, he put a value of 8 in the comparison matrix. The $d_3^+$ to $d_3^-$ comparison element would then automatically get a value of 1/8.

| Importance of avoiding deviation from target hours | $d_1^-$ | $d_1^+$ | $d_2^-$ | $d_2^+$ | $d_3^-$ | $d_3^+$ |
|---|---|---|---|---|---|---|
| $d_1^-$ | 1 | 1/7 | 1 | 1 | 1/5 | 1 |
| $d_1^+$ | 7 | 1 | 5 | 5 | 2 | 7 |
| $d_2^-$ | 1 | 1 | 1 | 1 | 1/5 | 2 |
| $d_2^+$ | 1 | 1/5 | 1 | 1 | 1/5 | 2 |
| $d_3^-$ | 5 | 1/2 | 5 | 5 | 1 | 8 |
| $d_3^+$ | 1 | 1/7 | 1/2 | 1/2 | 1/8 | 1 |

Figure 6. Pairwise Comparisons for Deviation Variables

The 'eigenvalue method' was used to determine the relative weights of the second priority level goals from the pairwise comparisons. A detailed description of the calculations used in this method can be found in (71). The weights obtained (shown in Table 2) were used as the coefficients in the objective function, Eq (3.22).

Table 2. Objective Function Weights for Example Problem

| Deviation Variable | Weight |
|---|---|
| $d_1^-$ | 0.063 |
| $d_1^+$ | 0.421 |
| $d_2^-$ | 0.074 |
| $d_2^+$ | 0.074 |
| $d_3^-$ | 0.321 |
| $d_3^+$ | 0.047 |

Next, the AHP was used to determine the values of the technical coefficients, $c_{ip}$. Figure 7 shows the decision hierarchy used by Lt Matickle.

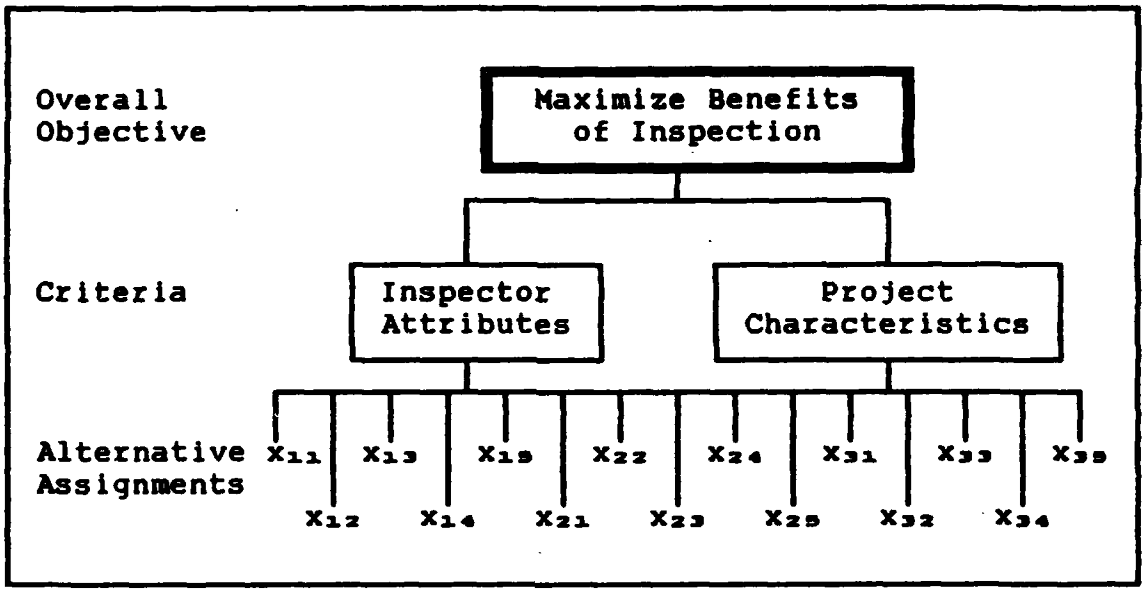


*Figure 7. Hierarchy for Inspector Assignments*

The weights calculated by the AHP were translated into the utility coefficients using Eqs (2.4), (2.5) and (2.6). These values were multiplied by a factor of ten to obtain coefficients between 0 and 10 - the magnitude recommended by Williams (86:33). The constants b and a were calculated as shown below.

$$b = 1/(\text{best} - \text{worst}) = 1/(.137 - .020) = 8.547 \qquad (3.11)$$

$$a = -b * \text{worst} = -8.547 * .020 = -0.171 \qquad (3.12)$$

The AHP weights and the coefficients are shown in Table 3.

Table 3. AHP Weights and Coefficient $c_{ip}$ Values

| Alternative | Inspector | Project | AHP Weight | Coefficient $c_{ip}$ |
|---|---|---|---|---|
| 1,1 | Carl | Pave Roads | 0.137 | 10.00 |
| 1,2 | Carl | HVAC | 0.031 | 0.94 |
| 1,3 | Carl | TEMPEST | 0.118 | 8.38 |
| 1,4 | Carl | Computer | 0.036 | 1.37 |
| 1,5 | Carl | NCO Club | 0.074 | 4.62 |
| 2,1 | Hank | Pave Roads | 0.053 | 2.12 |
| 2,2 | Hank | HVAC | 0.108 | 7.52 |
| 2,3 | Hank | TEMPEST | 0.020 | 0.00 |
| 2,4 | Hank | Computer | 0.050 | 2.56 |
| 2,5 | Hank | NCO Club | 0.074 | 4.62 |
| 3,1 | Keith | Pave Roads | 0.060 | 3.42 |
| 3,2 | Keith | HVAC | 0.031 | 0.94 |
| 3,3 | Keith | TEMPEST | 0.034 | 1.20 |
| 3,4 | Keith | Computer | 0.112 | 7.86 |
| 3,5 | Keith | NCO Club | 0.060 | 3.42 |

The 'maximize quality' goal was determined using 75 percent of the maximum possible quality value, Umax. This value was calculated by solving the following equations:

Maximize

$$U_{max} = \Sigma(c_{ip} * x_{ip}) \quad (i = 1, 2, 3, \; p = 1, 2, 3, 4, 5) \tag{3.13}$$

Subject to

$$x_{11} + x_{12} + x_{13} + x_{14} + x_{15} \leq 100 \tag{3.14}$$

$$x_{21} + x_{22} + x_{23} + x_{24} + x_{25} \leq 140 \tag{3.15}$$

$$x_{31} + x_{32} + x_{33} + x_{34} + x_{35} \leq 160 \tag{3.16}$$

$$x_{11} + x_{21} + x_{31} \geq 20 \tag{3.17}$$

$$x_{12} + x_{22} + x_{32} \geq 20 \tag{3.18}$$

$$x_{13} + x_{23} + x_{33} \geq 20 \tag{3.19}$$

$$x_{14} + x_{24} + x_{34} \geq 20 \tag{3.20}$$

$$x_{15} + x_{25} + x_{35} \geq 20 \tag{3.21}$$

where

$x_{ip}$ = the number of hours inspector i spends inspecting project p per month

$c_{ip}$ = the technical coefficient associated with alternative i,p

The goal programming formulation can be represented by

Minimize

$$Z = P1*d_4^- + 0.063*P2*d_1^- + 0.421*P2*d_1^+ + 0.074*P2*d_2^- + 0.74*P2*d_2^+ + 0.321*P2*d_3^- + 0.047*P2*d_3^- \quad (3.22)$$

Subject to

$$x_{11} + x_{12} + x_{13} + x_{14} + x_{15} \le 100 \quad (3.14)$$

$$x_{21} + x_{22} + x_{23} + x_{24} + x_{25} \le 140 \quad (3.15)$$

$$x_{31} + x_{32} + x_{33} + x_{34} + x_{35} \le 160 \quad (3.16)$$

$$x_{11} + x_{21} + x_{31} \ge 20 \quad (3.17)$$

$$x_{12} + x_{22} + x_{32} \ge 20 \quad (3.18)$$

$$x_{13} + x_{23} + x_{33} \ge 20 \quad (3.19)$$

$$x_{14} + x_{24} + x_{34} \ge 20 \quad (3.20)$$

$$x_{15} + x_{25} + x_{35} \ge 20 \quad (3.21)$$

$$x_{11} + x_{12} + x_{13} + x_{14} + x_{15} + d_1^- - d_1^+ = 25 \quad (3.23)$$

$$x_{21} + x_{22} + x_{23} + x_{24} + x_{25} + d_2^- - d_2^+ = 125 \quad (3.24)$$

$$x_{31} + x_{32} + x_{33} + x_{34} + x_{35} + d_3^- - d_3^+ = 80 \quad (3.25)$$

$$\Sigma(c_{ip} * x_{ip}) + d_4^- - d_4^+ = 2393$$

$$(i = 1, 2, 3;\ p = 1, 2, 3, 4, 5) \quad (3.26)$$

where

$d_i^-$ and $d_i^+$, (i = 1, 2, 3) = inspection hours under- and over- assigned to inspector i

$d_4^-$ and $d_4^+$ = the under- and over- achievement of the maximize quality goal

$x_{ip}$ = the number of hours inspector i spends inspecting project p per month

$c_{ip}$ = the technical coefficient associated with alternative i,p

One problem solution (there were alternative optimal solutions) is shown in Figure 8.

| INSPECTOR i | PROJECT p: Pave Roads | Install HVAC | TEMPEST | New Computer | Renovate NCO Club |
|---|---|---|---|---|---|
| Carl | 0 | 0 | 27 | 0 | 0 |
| Hank | 0 | 120 | 0 | 0 | 20 |
| Keith | 20 | 0 | 0 | 140 | 0 |

Figure 8. Example Solution, Inspector Hours per Project

This solution indicates Carl should inspect the TEMPEST project, Hank should inspect the Install HVAC and Renovate NCO Club projects, and Keith should inspect the New Computer and Pave Roads projects.

One interesting note about this result is that the very large, important, Pave Roads project would only be inspected 20 hours per month by the relatively inexperienced inspector Keith. The model was not able to assign the project to Carl because his limited man-hours were better used to inspect the TEMPEST project. The Pave Road project's high importance is not enough to offset the fact that Keith is better suited to the Install Computer project. Also, Keith is preferred over Hank as the Pave Roads inspector. So, in effect, the model solution implies the highest payback per inspection hour is to use Keith to inspect the computer project. The CM would have to reevaluate the model assignments and could change the assigned weights if he was uncomfortable with the results.

# IV. Model Evaluation

The chapter evaluates the model formulated in chapter III in two stages - an application to a specific organization, and an analysis of the model developed in the application.

The model was applied to a construction inspection section at Wright-Patterson Air Force Base (WPAFB). This application involved tailoring the baseline model to the organization's decision environment. The desires and judgements of the WPAFB CM were input into the model.

During the second stage, the model form that evolved during the test application and its solution were evaluated against several criteria suggested in the literature.

## Model Application

Organizational Environment of Test Inspection Section. Wright-Patterson's Contract Management Section divides the construction inspection workload into two construction inspection sections. Projects are assigned according to their location on base. One of these sections was used for the test. At the time of this study, the section had six inspectors plus the section chief, Mr. James Earnhardt (12). They had approximately 40 projects under construction.

Test Assumptions. To fully test the model, it was decided to allow the assumption that the CM could assign inspectors without regard to their current assignment. The model could be then evaluated against the assignments the CM actually made. This assumption helped overcome two application difficulties - constraints due to current assignments and difficulties in applying the model to future projects. The implications of the assumption are discussed later in this chapter.

Current Assignment Constraints. As the initial information for the test was gathered, it became apparent the inspector assignment decision found in the field would violate a premise of the baseline model. Rarely would the CM have the opportunity to 'start from scratch' and make the inspector assignments for all the projects at the same time. Instead, at any one time, most of the assignments would already be made and the CM would only make assignments as new projects began.

The model still applies to this situation, there would just be relatively few decision variables. Additionally, the CM could use the model for other purposes as described in Chapter V.

Future Project Unfamiliarity. It was difficult for Mr Earnhardt to include future projects in the model. WPAFB is a large base with a complex construction program and the CM was unfamiliar with many of the projects not scheduled to begin in the near future. In order for Mr. Earnhardt to be able to properly make judgements, it was decided to use current projects that were less than 95 percent complete as the test data base. Projects over 95 percent complete were not used since most of them were scheduled to be completed within the test period.

Model Refinement. The parameters of the WPAFB model were developed following steps similar to the development of the baseline model:

1. Evaluation and selection of decision variables.
2. Evaluation and selection of goal and objective equations.
3. Calculation of the equation coefficients.
4. Determination of priorities and weights.
5. Stating model in a mathematical form.

Decision Variables. The baseline model used $x_{ip}$, the number of hours inspector i spent inspecting project p. However, Mr. Earnhardt based his decisions on the number of projects an inspector was assigned, not on the amount of hours he spent inspecting. If the test model used hours instead of projects, the goal and constraint equations would have required a conversion of the number of projects into hours inspected.

To avoid this, a zero-one goal programing model was used for the test. Zero-one goal programming is used when the value of some or all of the decision variables must be zero or one in the solution (76: 102). In the WPAFB model, the decision variable $x_{ip}$ equals 1 if inspector i is assigned to project p, and 0 otherwise. The total number of projects assigned each inspector can then be directly represented in the goal and constraint equations.

Goal and Constraint Equations. The 'maximize quality' goal was retained. Mr. Earnhardt believed the model should attempt to obtain the maximum possible value for the 'maximize quality' goal. He did not have any opinions on an acceptable percentage to use for the maximum possible 'maximize quality' goal. This was reasonable since he had never used the model before. It was decided to use 100 percent of the maximum value to solve the model and then vary the allowable percentages to test the possible affect of the uncertainty.

Mr. Earnhardt had no set absolute maximum or target number of projects per inspector. Instead, he preferred to try to even out the work load among the inspectors as much as possible. He normally assumed all projects created about the same amount of work during any one time period. He felt this assumption was reasonable because there are several tasks that must be done on each project and larger projects tend to cause approximately the same workload per period, just over a larger number of periods. His desire to assign each inspector the same number of projects seems appropriate. With 38 projects and six inspectors, the workload would then be 6.33 projects per inspector. A RHS value of 6.5 was used to reflect the decision that the assignment of either six or seven projects was equally preferable.

He did not have a requirement to assign alternate inspectors to projects. This implies each project should have one and only one inspector assigned to it.

Coefficient Values. The next step was to determine the values of the 'maximize quality' goal function coefficients using the AHP. The CM felt the value of the inspection effort was almost completely dependant on the inspector to project combination. Unlike the Chapter III example problem that included both the inspector to project relationships and the project characteristics (see Figure 7), the test model used only the value of the inspector/project match up. Mr. Earnhardt felt the project importance or other characteristics did not influence his assignment decisions. He found every project tended to be considered equally important and that any other project characteristics could be included in the inspector to project considerations.

Mr. Earnhardt then performed pairwise comparisons by filling out the form shown in Figure 9, indicating the preference of each inspector for each project. The values were used to calculate relative weights. The normalized weights resulting from the AHP were converted to utility values and then into the inspector utility coefficients as described in Chapter III. An example calculation of the $c_{ip}$ value is given in Appendix A.

p, Project #: _______

Contract #: _______

Project(s): _______

Cost: $______

| Inspector | AAAAA | BBBBB | CCCCC | DDDDD | EEEEE | FFFFF |
|---|---|---|---|---|---|---|
| i = | 1 | 2 | 3 | 4 | 5 | 6 |

Column

| Project ___ | AAAAA | BBBBB | CCCCC | DDDDD | EEEEE | FFFFF |
|---|---|---|---|---|---|---|
| ROW AAAAAA | 1 | # | # | # | # | # |
| BBBBBB | | 1 | # | # | # | # |
| CCCCCC | | | 1 | # | # | # |
| DDDDDD | | | | 1 | # | # |
| EEEEEE | | | | | 1 | # |
| FFFFFF | | | | | | 1 |

When choosing an inspector for above project, inspector in row (on left) is *____________ compared to the inspector in column (on top). If inspector in COLUMN is preferred, use 1/value.

* Use one of the values below:

1 = EQUALLY PREFERRED
2
3 = SLIGHTLY MORE PREFERRED
4
5 = STRONGLY MORE PREFERRED
6
7 = VERY STRONGLY MORE PREFERRED
8
9 = EXTREMELY MORE PREFERRED

Figure 9. Pairwise Comparison Form for WPAFB Test

*Weights and Priorities*. Mr. Earnhardt considered maximizing the benefits of inspection (the 'maximize quality' goal) his top priority. He felt this objective should be accomplished above any other model goal. In goal programming terminology, he considered it preemptively more important than the set of goals associated with evenly dividing the workload.

The value for Umax, the aspiration level of the 'maximize quality' goal, was determined by solving Eqs (4.1) to (4.3).

Maximize

$$\Sigma(c_{ip} * x_{ip}) = \text{Umax} \quad (i = 1, 2, \ldots, 6; \; p = 1, 2, \ldots, 38) \tag{4.1}$$

*Subject to:*

$$\sum_{i=1}^{I} x_{ip} = 1 \quad (p = 1, 2, \ldots, 38) \tag{4.2}$$

$$c_{ip} \geq 0$$

$$x_{ip} = 0 \text{ or } 1 \text{ for all } i \text{ and } p \tag{4.3}$$

where

$$x_{ip} = \begin{cases} 1 & \text{if inspector } i \text{ is assigned to project } p, \\ 0 & \text{otherwise} \end{cases}$$

$c_{ip}$ = value of inspector i inspecting project p as determined from the AHP

A value of 343 was obtained for Umax.

The CM thought the aspiration of a balanced workload was equally important for every inspector. For example, he felt attempting to assign inspector 1 the fair workload of six or seven projects was equally preferred to trying to assign inspector 2 six or seven projects. The same would be true for each comparison between inspectors. Additionally, he considered avoiding under-working and overworking inspectors equally important. This resulted in the weights of the deviation variables for the second level goals all being equal to one in the objective function.

Mathematical Form. The model can be summarized in the following mathematical form

Minimize

$$Z = P1d_1^- + \sum_{q=2}^{7} P2(d_q^- + d_q^+) \qquad (4.4)$$

Subject to:

$$\Sigma(c_{ip} * x_{ip}) + (d_1^- - d_1^+) = \%Umax$$

$$(i = 1, 2, \ldots, 6;\ p = 1, 2, \ldots, 38) \qquad (4.5)$$

$$\sum_{p=1}^{38} x_{ip} + (d_q^- - d_q^+) = 6.5 \quad (i = 1, 2, \ldots, 6;$$

$$q = i+1, i+2, \ldots, 7) \qquad (4.6)$$

$$\sum_{i=1}^{I} x_{ip} = 1 \quad (p = 1, 2, \ldots, 38) \qquad (4.7)$$

$$c_{ip},\ d_q^-,\ d_q^+ \geq 0$$

$$x_{ip} = 0 \text{ or } 1 \text{ for all } i \text{ and } p \qquad (4.8)$$

where

P1, P2 = preemptive priorities, and P1 >>> P2

$$x_{ip} = \begin{cases} 1 & \text{if inspector } i \text{ is assigned to project } p, \\ 0 & \text{otherwise} \end{cases}$$

$c_{ip}$ = value of inspector i inspecting project p

$d_1^-$, $d_1^+$ = under- and over-achievement of 'maximize quality' goal

$d_q^-$, $d_q^+$ = number of projects assigned inspector q

(q = i-1) above or below the even workload goal

%Umax is a percentage of the Umax value

## Evaluation of Refined Model

The test model as developed above was solved and then evaluated to assess the value of goal programming as a decision tool for the CM. The model was judged in the following areas:

1. Model Solution.
2. Ease of understanding and using the model.
3. Model structure.
4. Model logic and response.
5. Input Data.

Model Solution. The first step in evaluating the model as applied to WPAFB was to solve Eqs (4.4) to (4.8). This provided one measurement of the model's ability to accurately simulate the decision process of an experienced CM. Three versions of the model were solved using 100, 90, and 80 percent of Umax. The results of the model solution are shown in Figure 10. The total at the bottom shows the total number of projects assigned the inspector for each version. The solution shows the 100 percent UMax solution exactly matched the selections by Mr. Earnhardt. This perfect match of 228 assignments requires some further explanation.

Since projects currently under construction were used for the test, Mr. Earnhardt had already assigned inspectors to the projects. Due a to misunderstanding, Mr. Earnhardt performed the pairwise comparisons in accordance with those 'a priori' assignments. This introduced substantial bias to the AHP weights with groups of projects having one inspector with much higher rankings than the others. These biased weights resulted in a dominant inspector utility value for each project grouping. When the model sought the optimal assignments, these dominant $c_{ip}$ values drove it to the obvious alternatives.

Ease of Understanding and Using Model. The test at Wright-Patterson revealed that the effort and knowledge required to use the model in its applied form may make it less effective as a decision tool. For example, the capability of the model to be used for sensitivity and 'what if' analysis depends on how well the CM understands the concepts of mathematical programming. Most CM's do not have a background in mathematical programming. This could make solutions, especially sensitivity analysis, difficult to use. These operations were not time consuming because computer programs can be used to solve the model and perform other analysis. They do, however, require the model user to have a relatively thorough understanding of the concepts behind them.

Inspector

| Project | 1 | | | | 2 | | | | 3 | | | | 4 | | | | 5 | | | | 6 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | A | B | C | D | A | B | C | D | A | B | C | D | A | B | C | D | A | B | C | D |
| 1 | | | | | | | | | | | | | | | | | | | | | X | X | X | X |
| 2 | | | | | | | | | | | | | | | | | | | | | X | X | X | X |
| 3 | | | | | | | | | | | | | | | | | | | | | X | X | X | X |
| 4 | | | | | | | | | | | | | | | | | | | | | X | X | X | X |
| 5 | | | | | | | | | | | | | | | | | X | X | X | X | | | | |
| 6 | | | | | | | | | | | | | | | | | X | X | X | X | | | | |
| 7 | | | | | | | | | | | | | | | | | X | X | X | X | | | | |
| 8 | | | | | | | | | | | | | X | X | X | X | | | | | | | | |
| 9 | | | | | | | | | | | | | X | X | X | X | | | | | | | | |
| 10 | | | | | | | | | | | | | X | X | X | X | | | | | | | | |
| 11 | | | | | | | | | | | | | X | X | X | X | | | | | | | | |
| 12 | | | | | | | | | | | | | X | X | X | X | | | | | | | | |
| 13 | | | | | | | | | X | X | X | X | | | | | | | | | | | | |
| 14 | | | | | | | | | X | X | X | X | | | | | | | | | | | | |
| 15 | | | | | | | | | X | X | X | X | | | | | | | | | | | | |
| 16 | | | | | | | | | X | X | X | X | | | | | | | | | | | | |
| 17 | | | | | | | | | X | X | X | X | | | | | | | | | | | | |
| 18 | | | | | | | | | X | X | X | X | | | | | | | | | | | | |
| 19 | | | | | | | | | X | X | X | X | | | | | | | | | | | | |
| 20 | | | | | | | | | X | | | X | | | | | | X | X | | | | | |
| 21 | | | X | | | | | | X | | | X | | | | | | X | | | | | | |
| 22 | | | | | X | X | X | X | | | | | | | | | | | | | | | | |
| 23 | | | | | X | X | X | X | | | | | | | | | | | | | | | | |
| 24 | | | | | X | X | X | X | | | | | | | | | | | | | | | | |
| 25 | | | | | X | X | X | X | | | | | | | | | | | | | | | | |
| 26 | | | | | X | X | X | X | | | | | | | | | | | | | | | | |
| 27 | | | | | X | X | X | X | | | | | | | | | | | | | | | | |
| 28 | | | | | X | X | X | X | | | | | | | | | | | | | | | | |
| 29 | | | | | X | X | | X | | | | | | | | | | | X | | | | | |
| 30 | | | | | X | | | X | | | | | | | | | | X | X | | | | | |
| 31 | X | X | X | X | | | | | | | | | | | | | | | | | | | | |
| 32 | X | X | X | X | | | | | | | | | | | | | | | | | | | | |
| 33 | X | X | X | X | | | | | | | | | | | | | | | | | | | | |
| 34 | X | X | X | X | | | | | | | | | | | | | | | | | | | | |
| 35 | X | X | X | X | | | | | | | | | | | | | | | | | | | | |
| 36 | X | X | | X | | | | | | | | | | | X | | | | | | | | | |
| 37 | X | X | | X | | | | | | | | | | | | | | | | | | | X | |
| 38 | X | | | X | | | | | | | | | | X | | | | | | | | | X | |
| Total | 8 | 7 | 6 | 8 | 9 | 8 | 7 | 9 | 9 | 7 | 7 | 9 | 5 | 5 | 6 | 5 | 3 | 6 | 6 | 3 | 4 | 4 | 6 | 4 |

A = 100% Umax
B = 90% Umax
C = 80% Umax
D = CM's selections

Figure 10. Assignments from WPAFB Test Model Results

Few difficulties were encountered in understanding and making the paired comparisons. One negative aspect, however, was that the number of paired comparisons required can get quite large. In the test model, 38 comparison matrices, one for each project, were accomplished. Additional matrices would have been necessary if the deviation weights were not all equal and/or if other factors such as project size and importance were included in the determination of technical coefficients. In fact, if there are n elements, the number of judgements required equals $[(n * n) - n]/2$ (69:80). For instance, a model including deviation weights for each of the goal equations and an additional factor (such as project characteristics) for the $c_{ip}$ determination would require at least 793 more judgements. Mr. Earnhardt simplified the process by grouping similar projects into groups and using one matrix for each group. This seems reasonable, however, some of the implications of the groupings are given in the discussion on model logic and response.

The use of an additional set of equations to determine the initial Umax values also made the model solution more cumbersome.

<u>Model Structure</u>. A good model structure contains only the most basic factors and operations of the system, yet has enough detail to give satisfactorily results (31:38). The

level of detail in both decision variables and type and number of constraints is important.

Only those factors whose effects help to identify the relative desirability of the alternatives should be included in a model (25:772). The WPAFB model seems to have captured those crucial factors. The key factors that drive the inspector assignment appear to be the relationships between the projects' characteristics and the inspectors' attributes. The desired inspector workload also affects the model solution.

It is reasonable that additional project variables could be included. For instance, some CM's may feel the project's size, complexity, importance or some other project characteristic will affect the amount of inspection required and result in different workload goals.

Since the model results matched Mr. Earnhardt's selections, the use of one measure of the inspector's attributes, $c_{ip}$, appears to capture enough of the important relationships. This means more specific variables such as training level, years experience, personal characteristics, etc. are not necessary. However, any conclusions drawn from the test solution obviously are weakened by the bias of the test inputs.

At WPAFB, inspector assignments are often made by organizational unique rules and requirements. Without this constraint, all projects scheduled for the Headquarters Air

Force Logistic Command (HQ AFLC) buildings are assigned to one inspector. Once that inspector was chosen (it is inspector 1), the CM was constrained to use the same inspector for all the HQ AFLC projects. For example, without that constraint Mr. Earnhardt felt that inspector 4, not inspector 1, should be assigned project 33. Mr. Earnhardt overcame this by giving inspector 1 very high preference rankings for the HQ AFLC projects. A more appropriate way to make these exclusionary type assignments would be to use the zero-one goal programming structure and assign a value of 1 for all $x_{ip}$ for the inspector where the project is an HQ AFLC project.

Perhaps the most important discovery during the test is that the basic model structure is somewhat flawed. As noted earlier, the CM will probably not be able to make all of the assignments at once. The concepts of the model still apply, but when dealing with only one or two assignments at a time, it is less valuable.

Model Logic and Response. This area of evaluation involved appraising the model's ability to accurately and logically represent interrelationships and interactions between elements. This includes two basic model influences: the inspector/project relationship represented by $c_{ip}$, and the weights of the deviation variables associated with each goal.

It is not necessary for the model to find an optimal or even completely accurate solution. As Hillier and Lieberman explain:

> The proper criterion for judging the validity of a model is whether or not it predicts the relative effects of the alternative courses with sufficient accuracy to permit a sound decision [25:772].

For instance, the calculation of the true value of Umax is not critical since its only purpose is to judge the relative desirability of the various assignment alternatives.

Inspector to Project Relationship. The inspector to project relationship was represented by the variable $c_{ip}$. The correctness of the solution obtained by the model depends intimately on the proper derivation of the $c_{ip}$ values.

One way to assess the logic and responsiveness of the relationship was by measuring the changes in the solutions caused by varying the RHS value of the 'maximize quality' goal (the value of %Umax).

As the value of Umax was lowered, the model was able to more completely meet the CM's desires to equally distribute the workload. This is logical since it represents a willingness to trade-off some of the benefits of inspection quality for a more evenly divided workload. As Figure 10 shows, the model was able to fully attain the goal of either six or seven projects per inspector when using a RHS value of 80 percent of Umax.

The effect of varying the $c_{ip}$ values themselves was also evaluated. As a $c_{ip}$ was given a higher or lower value, the model solution responded in the logical direction.

For example, the pairwise comparisons for project 38 are shown in the first part of Appendix B. A new comparison ranking was made for project 38 and is shown in the second part of Appendix B. The new ranking changed the value of $c_{6,38}$ from 0.5 to 1.95, and the value of $c_{4,38}$ from 1.96 to 1.18. With Umax at the 90 percent level, this resulted in the model switching the assignment of project 38 from inspector 4 to inspector 6. The sensitivity of the model to changes in the value of $c_{ip}$ depended greatly on which $c_{ip}$ value was being altered. Most projects had a 'dominant' $c_{ip}$ value, one whose value was much higher for one inspector compared to the other inspectors. Because the model attempted to assign projects to the dominant inspector/project combinations as much as possible, changes in the $c_{ip}$ values associated with these assignments quickly caused changes in the model solution. Changes in the 'non-dominant' $c_{ip}$ values were influential in the model solution only when the %Umax valued was lowered enough to allow attainment of the lower priority workload goals.

The existence of the dominant $c_{ip}$ values is due to Mr. Earnhardt's grouping similar projects together as mentioned earlier. The bias exaggerated the dominance.

Goal Weights. The WPAFB model did not use weighted deviation variables. Additional tests run with trial goal weights responded in the proper direction (or did not change) for each test. The model attempted to assign exactly the 'fair share' of 6 or 7 projects first to inspectors with higher deviation weights, with less concern for inspectors with lower deviation weighs. The model was relatively sensitive to changes in the weights in runs that used high %Umax values and insensitive in those runs with low %Umax values.

Input Data. To appraise the value of the input data, both the information obtained directly from the CM and the data input into the model that was the result of some transformation process must be evaluated.

The input data used in the test model included:

1. Pairwise comparison entries.
2. UMax levels.
3. Weights and priorities of goals.
4. Hierarchy Factors.

Pairwise Comparison Entries. As described earlier, the test required Mr. Earnhardt to complete 38 pairwise comparison matrices using the form shown in Figure 9. The numbers were translated to AHP weights and then into $c_{ip}$ values. The model solution indicates the comparison data properly represents the CM's judgements. However, any conclusions must be made cautiously since the bias introduced into the model helps drive the model toward the correct representation.

The comparisons were also checked for the consistency to measure how well the decision maker's judgements relate to one another. The consistency ratios calculated ranged from 0.098 to 0.118. Saaty feels that a value above 0.10 may be an indication that the judgement should be revised (69:16-18,83). However, it appears that the judgments are consistent enough so that revisions made to bring the consistency ratio to below 0.10 would not affect the models solution.

UMax Values. The model requires the CM to select appropriate %Umax levels. The quality of this judgement could significantly affect the model solution.

As noted above, Mr. Earnhardt understandably had no real feel for an acceptable percent of Umax to use for the 'maximize quality' goal. This would probably typical in any application of the model. However, by performing 'what if' analysis with varying %Umax values, the CM could evaluate the tradeoffs associated with the different achievement levels.

Goal Weights and Priorities. The construction management chief must also provide judgement on the goal priorities and weights. The test model did not use weighted deviation variables. However, the use of the CM's priority structure, even without any guidance from his superiors, should be a good basis for the inspector assignment decision. The CM, like most mid-level managers in bureaucratic organizations, should tend "to work toward the most efficient achievement of organizational objectives" (43:34). The use of the AHP to assist the CM in determining weights will also help appropriately represent the organization's goals.

One possible problem area with the use of a preemptive priority is whether it is truly preemptive. In the test model, Mr. Earnhardt had confidence that the 'maximize quality' goal was preemptively more important than obtainment of an equal workload. It seems reasonable, however, that another CM might feel a slight degradation in the quality level is acceptable if it results in a significant increase in the attainment of another objective. Even if he originally felt the quality goal should be maximized before trying to achieve another goal, his actual decision process may allow some trade-offs between the goals.

Hierarchy Factors. The final model input is the selection of the specific factors included in the AHP hierarchy for the inspection utility calculation. The decision maker would also be responsible for making this determination. As mentioned in the earlier description of coefficient value determination, the WPAFB model did not include any other criteria other than the inspector to project relationship. Having the CM select the criteria is considered appropriate for the same reasons given above for the selection of weights and priorities. After the factors are selected, they must be placed in a hierarchial structure. A CM without training or assistance from an expert may have difficulty setting up the hierarchy. The hierarchy used for the WPAFB test appears to suitably represent Mr. Earnhardt's decision process the section since the model's response resulting from the hierarchy was proper.

# V. Conclusions and Recommendations

This research assessed goal programming as a decision tool for the Air Force Chief of Construction Management in assigning inspectors to projects to obtain the optimal benefits from the available inspection capabilities. A review of the literature indicated goal programming was a viable method and that it had been applied to similar human resource planning applications. This chapter summarizes the results and conclusions from the analysis and testing of a goal programming model developed to evaluate the method. Recommendations for further research are also presented.

## Summary of Results and Conclusions

This research confirms goal programming's ability to represent the inspector assignment problem. The goal equations and rigid constraints developed from the literature review and model testing captured the basic relationships of the decision process. Although the results of the test model must be tempered with the realization the input data was substantially biased, the researcher feels the model still would have performed well using unbiased input from a CM. The remainder of this discussion is based on that assumption.

Model Structure. Despite the success of the model's simulation efforts, a basic difference in the model and the actual decision process was highlighted during the test. In practice, the decision does not typically involve the assignment of all the inspectors to all the ongoing projects. Instead, most of the assignments would already be made at any one point in time and the CM would usually just make assignments as new projects begin. A goal programming model could still be used for the decision. However, there are fewer advantages of using mathematical modelling when the problem has a relatively small number of decision variables. Additionally, goal programming could be used for planning, evaluating current assignments, and helping new CM's understand the intricacies of the decision.

A zero-one goal programming model with the decision variable $x_{ip}$, where $x_{ip}$ equals one if project p is assigned to inspector i and zero otherwise, was used in the WPAFB test. The zero-one form allowed the model to allocate inspectors' workload according to the total number of projects (versus by total inspection hours) and better represent the CM's decision process. Additionally, the use of zero-one goal programming allows the decision maker to make exclusive type assignments. That is, he can assign $x_{ip}$ a value of zero if he wants to exclude that assignment alternative or a value of one if he wants to ensure inspector i is assigned project p.

The test model performed well when its solution assignments were compared to the CM's choices. In fact, they matched exactly. The model also responded logically when the RHS and coefficient values were varied.

The key factor in the model performance appears to be the correct determination of the $c_{ip}$ values, the relationships between the projects' characteristics and the inspectors' attributes.

The only necessary resource constraints appear to be those associated with the inspector workload. Also, hard constraints for the minimum number of projects per inspector do not appear necessary. The model's attempts to attain the 'maximize quality goal' cause it to assign as many projects to an inspector as possible.

The model assumes each project will create about the same amount of work, but could be easily expanded to include information on varying workloads caused by projects. Where the workload required for a specific project is dependant on the inspector assigned to it, it would be more difficult to represent. For instance, in the Chapter III example problem, the TEMPEST project might have imposed a heavier workload requirement on Keith than on Carl.

Likewise, the model assumes the workload factors are constant throughout the project's duration. The model could be also expanded into a multi-period model to incorporate fluctuating workloads.

This researcher is not convinced the use of preemptive priorities truly reflects most CMs' decision framework. There is probably often a willingness to accept a small degradation in a higher priority goal for a large improvement in a lower priority objective. Although the decision maker could evaluate these trade offs within the goal programming framework through 'what-if' analysis.

Model Inputs. The ability of the model to simulate the CM's decision depends critically on accurate data input.

Equation Coefficients. One data input is the measurement of the preference of one assignment alternative over another, the inspector utility coefficient $c_{ip}$.

The $c_{ip}$ value calculation process used utility type values derived from AHP inputs. The use of just one measure of the inspector's attributes, $c_{ip}$, appears to capture enough of the important relationships so that more specific variables such as training level, years experience, and personal characteristics are not necessary.

However, for the model to correctly model the organizational environment, the CM must know his inspectors' positive and negative attributes and have a good understanding of the scope and nature of the projects assigned. The model assumes the $c_{ip}$ value is constant from period to period. Although this assumption was not tested, it seems reasonable the relative values of the $c_{ip}$'s would remain constant enough not to effect the solution.

Weights, Priorities and the AHP. The AHP also appears to be an appropriate method of translating the CM's desires into model inputs. The exact match of the test model solution and the relatively consistent pairwise comparisons provide indications it can be used to replicate the CM's judgements.

The use of the construction management chief as the source of judgements on the goal priorities and weights should be a good basis for the inspector assignment decision.

One negative aspect of the AHP is that the number of paired comparisons required can get quite large.

Right-Hand Side Values. Another input is the RHS values for the rigid constraints and the goal equations.

The test model used %Umax, a percent of the maximum possible inspection utility value, as the RHS of the 'maximize benefits' goal equation. Since most CM's would not have a feel for an acceptable %Umax to use, an interactive method evaluating the tradeoffs associated with the different achievement levels would normally have to be used.

The calculation of the true value of Umax is not critical since its only purpose is to judge the relative desirability of the various assignment alternatives.

Application. Problems anticipated with an actual application include: inexperienced CMs having difficulties providing proper judgements, the lack of familiarity in decision models among CMs, the effort required to use the model correctly, and the uncertainties involved in future projects. Future project uncertainties are due to the possibility of changes in project scope and schedule between the time the project is originally approved for construction and its actual award date.

Adding to these difficulties is the limited software available for solving goal programming problems. The availability of software for zero-one goal programming or for use with microcomputers is particularly limited (54:344).

During this research, only three commercial goal programming packages for microcomputers were found, with capabilities ranging from a maximum from 10 to 40 constraints or variables. None of these packages included zero-one goal programming (35:487-509; 47:33-36; 80:16).

## Recommendations

The recommendations are grouped into two areas: recommendations involving the continued use of a goal programming model like the one developed in this thesis and additional recommendations involving the use of a method other than goal programming for the problem solution.

Goal Programming Recommendations. Although goal programming may not provide the final answer, it can simulate the CM's inspector assignment decision process. If another researcher believed a model similar to the one developed in this effort warranted additional investigation, the recommendations below are suggested areas for future research.

Application. For a goal programming or any other mathematical model to be of any practical value for the CM, much of the effort required to implement and use it would have to be automated.

The reduced data input effort from computerization of the model would increase the model's acceptance by users and decrease the chances of unintentional error. A computer package could be used to help the CM develop the appropriate hierarchial structure, RHS values, and technical coefficients for his base. In addition, with a 'user friendly' comprehensive computer package, even CM's with little goal programming knowledge could use the model for sensitivity and 'what if' analysis.

Much of the data appears compatible with computers making it possible to automate most of model and incorporate existing data bases. The goal should be to utilize intuitive judgement, but let the computer do the tedious tasks.

The model could be interfaced with the Base Civil Engineer's Work Information Management System (WIMS).

Model Structure. The model could be expanded to incorporate additional features including:

1. Historical data within the model's equations. For example, Huber describes a multiple regression model for a utility equation similar in use to the deterministic 'maximize quality' equation used in this research (27).

2. Manpower and workload forecasts.

3. Other work requirements that might be within the construction management section such as service contracts, readiness training, etc.

4. Behavioral factors, especially inspectors preferences.

5. Multi-period inspector assignments to incorporate workload fluctuations that might occur during different stages of the project.

6. Variations in the workload generated by a project among different inspectors.

Use of the Analytic Hierarchy Process. The Analytic Hierarchy Process is an excellent way of transforming the construction manager's judgements and preferences into a form suitable for use in a mathematical model.

The AHP would need to be automated, however, because of the large number of inputs that might be required in the decision hierarchy.

The AHP can also be used to obtain a good initial solution for a goal programming model (60).

Saaty and Vargas describe a process to evaluate the confidence level of the final ranking of alternatives. Their method uses probabilities based on the decision maker's uncertainties of the values he inputs during the AHP (73). This process could be integrated with the sensitivity analysis of the goal programming model.

Additional Recommendations. Overall, my strongest recommendation is to not use goal programming as the basis for the inspector assignment decision. This research has led me to believe the effort required to capture the decision purely within a mathematical format would not be worth the effort required to develop, implement and use the model in the field.

I recommend using heuristics obtained from experienced construction managers to capture the decision characteristics of the inspector assignment problem. It should be an automated system, perhaps using an expert system package. The model could incorporate goal programming and/or the AHP within it. For an example of using goal programming with heuristics see John Henderson's article on manpower planning (24:64).

Any model developed should include extensive validation by the review of construction managers in the field.

## Appendix A: Example Technical Coefficient Calculation

Mr. Earnhardt's pairwise comparisons of the alternative inspector to project assignments resulted in a AHP weight of 0.1570 for inspector 5 within the project 15 comparison matrix. This value was divided by 38, the number of comparison matrices, to obtain a normalized weight of 0.00413. The lowest normalized weight was 0.00134 and the highest was 0.01608.

The utility value was then calculated using Eqs (2.4), (2.5), and (2.6):

$$u = a + bw = -0.091 + 67.8 * 0.00413 = 0.189$$

where

$$b = 1/(\text{best} - \text{worst}) = 1/(0.01608 - 0.00134) = 67.8$$
$$a = -b * (\text{worst}) = -67.8 * 0.00134 = -0.091$$

Finally, the utility value was multiplied by 10 to obtain a value of 1.89 for the technical coefficient $c_{5,15}$.

## Appendix B: Example Pairwise Comparisons

### Actual Pairwise Comparison Test Values for Project 38

Inspector

INSPECTOR

| Project 38 | 1 | 2 | 3 | 4 | 5 | 6 | AHP Weight | $C_{ip}$ Value |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 7 | 7 | 7 | 7 | 7 | 0.550 | 8.91 |
| 2 | | 1 | 1 | 1/5 | 3 | 1 | 0.080 | 0.52 |
| 3 | | | 1 | 1/5 | 1 | 1 | 0.059 | 0.14 |
| 4 | | | | 1 | 1 | 1 | 0.161 | 1.96 |
| 5 | | | | | 1 | 1 | 0.071 | 0.36 |
| 6 | | | | | | 1 | 0.079 | 0.50 |

### Revised Pairwise Comparison Test Values for Project 38

Inspector

INSPECTOR

| Project 38 | 1 | 2 | 3 | 4 | 5 | 6 | AHP Weight | $C_{ip}$ Value |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 7 | 7 | 6 | 7 | 5 | 0.524 | 8.45 |
| 2 | | 1 | 1 | 1 | 1 | 1/5 | 0.065 | 0.25 |
| 3 | | | 1 | 1/5 | 1 | 1/5 | 0.051 | 0.00 |
| 4 | | | | 1 | 1 | 1 | 0.117 | 1.18 |
| 5 | | | | | 1 | 1 | 0.084 | 0.59 |
| 6 | | | | | | 1 | 0.160 | 1.95 |

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VITA

Captain James R. Schnoebelen [redacted] in 1978 [redacted] attended Iowa State University, from which he received the degree of Bachelor of Science in Civil Engineering in August 1983. He went on active duty in August of 1982 through the College Senior Engineering Program. Upon graduation from Iowa State, he attended Officer Training School and received his commission in the USAF in November of 1983. His initial assignment was to the 3480th Civil Engineering Squadron, Goodfellow AFB, Texas. He served as the Chief of Construction Management, Chief of Environmental and Contract Planning, and Chief of Resources and Requirements until entering the School of Systems and Logistics, Air Force Institute of Technology, in May 1987.

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Thesis Chairman: James R. Holt, Maj, USAF
Assistant Professor of Engineering Management

Thesis Reader: Mr. Douglas C. Osgood
Associate Professor of Contract Management


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thesis

The purpose of this ~~study~~ was to evaluate goal programming as a tool to assist the Chief of Construction Management (CM) assign inspectors to construction projects. Air Force construction projects represent a substantial investment. One way the CM can help insure construction projects are cost effective and high quality is through the efficient use of available resources - the abilities and time of his inspectors. Goal programming appeared to be an appropriate method to help assign inspectors so the CM could obtain the most value out of available inspector man-hours.

The evaluation of the model involved developing a general model and applying it to a test organization. The analytic hierarchy process (AHP) was used to translate the preferences and judgements of the CM into a form suitable for a mathematical model. The test confirmed goal programming's ability to represent the inspector assignment problem. The AHP was found to be an appropriate way to translate the CM's desires into model inputs. Despite the success of the model's simulation efforts, a basic difference in the model and the actual decision process was highlighted during the test application. In practice, the CM is constrained to the assignments already made and would only make additional assignments as new projects begin. Goal programming could still be used within these constraints. However, there are fewer advantages of using a mathematical model when the problem has a relatively small number of decision variables.

The author provides recommendations for continued research in applying goal programming to the inspector assignment decision. However, because of the great deal of effort that would be required to implement a goal programming model, the author's overall recommendation is to concentrate further research on methods other than goal programming. Among the other recommendations provided is to automate the heuristics used by experienced CMs.



WILLIAM A. MAUER 17 Oct 88
Associate Dean
School of Systems and Logistics
Air Force Institute of Technology (AU)
Wright-Patterson AFB OH 45433